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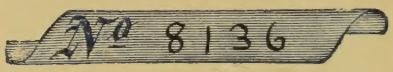

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THE BECQUEREL RAYS
AND THE PROPERTIES OF RADIUM

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AND THE PROPERTIES OF

RADIUM

BY

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PREFACE

In writing this book, my object has been to give as clear and simple an account of the phenomena of radio-activity as the subject admits of, without sacrificing accuracy. The extraordinary properties of radium have excited general interest outside the scientific world, and there are probably many who would be glad to learn something of the subject, if they could find it explained without the use of technicalities. However essential mathematical methods may be in developing the subject, they are seldom really necessary in presenting the results. Moreover, some idea of the train of reasoning can generally be given in ordinary language.

I have not found it possible to avoid assuming some elementary scientific knowledge on the part of the reader, but this has been reduced to the smallest limits, and probably a great part of the book will be intelligible without it.

I have not attempted to describe all the phenomena which have been recorded, but have confined

myself to those which seemed most significant and interesting.

In revising the book, I have had the advantage of consulting Professor Rutherford's excellent treatise on 'Radio-activity,' which has recently appeared, and have adopted one or two valuable and suggestive remarks from it.

The names of authorities have not in all cases been given, and it has been thought unnecessary, in view of the general character of the work, to give references to original papers.

TERLING PLACE, WITHAM,
August 1904.

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CHAPTER I

ELECTRIC DISCHARGE IN HIGH VACUA

THE clue which led to the discovery of radio-activity was obtained from the study of electric discharge in high vacua; and knowledge gained in the same way has been indispensable in interpreting its phenomena. Before entering on the main subject of this book, it will be desirable, and indeed essential, to give some account of the phenomena which accompany the passage of electricity through rarefied gases. When an electric discharge passes through air at atmospheric pressure, a narrow, well-defined spark is observed to pass between the electrodes of the induction coil or electrical machine used to produce the discharge.

When, however, these electrodes are placed in an air-tight vessel, and the air withdrawn by means of a mercurial air-pump, a profound change in the character of the discharge takes place. The spark becomes broad and ill-defined as the air pressure is reduced. Thus, for instance, if a cylindrical tube is

FIG. 1.—Electric discharge at a moderately low pressure. The negative electrode *a* is a disc, and is separated by a small dark interval from the blue negative glow *c*. The glow along the rest of the tube to the anode *b* is, in air, a diffuse band of reddish light, *d*.

used, a glow spreads out from the two electrodes and fills the tube (fig. 1).

In this case the luminosity is spread over a large area. But by making the tube with a constriction in the middle (fig. 2), the glow is concentrated in the

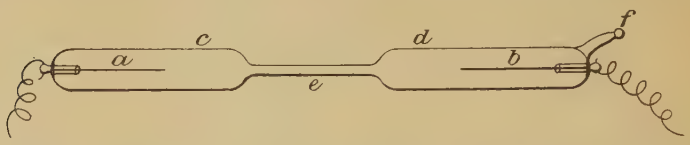

FIG. 2.—Plücker's tube, for examining the spectra of rarefied gases under electric discharge. The discharge passes between the platinum wires, *a*, *b*. These are sealed airtight into the elongated glass bulbs, *c*, *d*. The discharge is constricted, and increased in intensity by passing through the narrow tube *e*, which connects these bulbs. The gas is introduced at *f*, which can then be sealed off if desired.

narrow portion, and its brightness greatly increased. Such tubes are very useful for examining the spectrum of any desired gas under the electric discharge. They are known by the name of Plücker, who was the first to use them.

In the majority of gases the glow is most conspicuous at a pressure of about $\frac{1}{200}$ of an atmosphere.

Let us take the case of atmospheric air. In this case, at $\frac{1}{200}$ of the atmospheric pressure, the negative electrode is seen to be surrounded by a blue glow, different in colour from the reddish colour along the length of the spark. The same thing can be seen in the spark at atmospheric pressure, though in this case the glow is almost confined to the surface of the negative electrode. At the low pressure it can be seen that the blue negative glow is separated by a small dark interval from the electrode itself (see fig. 1).

Let the exhaustion now be carried further. It will be found that the blue negative glow spreads out and that the dark space becomes broader. A green luminosity begins to be visible on the wall of the tube opposite the negative electrode. At still higher exhaustions, such as can only be obtained by prolonged use of the mercurial pump, it is found that a sharp patch of green fluorescent light is visible on

the wall opposite to the negative electrode; this patch corresponds in shape to the electrode itself, if the electrode is flat. Thus a round disc electrode will produce a round patch only a little larger than itself. A faint streak of blue luminosity appears in the gas, stretching from the cathode to the phosphorescent spot. It is evident from these phenomena that some kind of influence is propagated out at right angles to the cathode surface and travels through the tube till it reaches the wall. This influence goes by

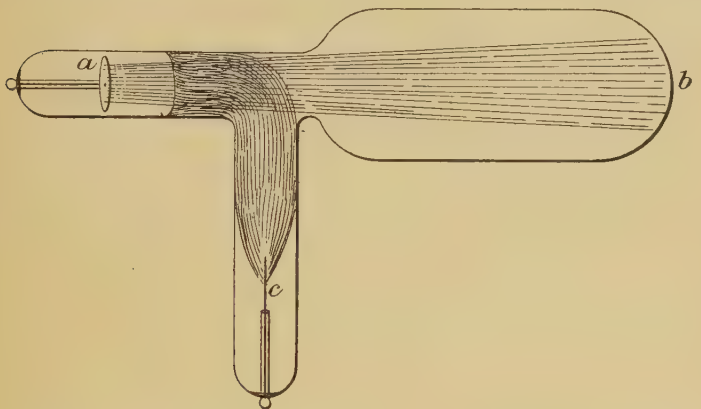

FIG. 3.—Experiment showing that the cathode rays are always emitted at right angles to the surface of the cathode, and do not necessarily follow the line of the discharge. The rays from the flat cathode, *a*, strike the wall of the tube at *b*, causing phosphorescence. They penetrate the glow of the main discharge, which curves away to the anode, *c*, in a lateral tube joined on to the main one.

the name of the cathode rays. The cathode rays always proceed at right angles to the cathode, whether that is the direction in which the anode lies or not. The spark or glow discharge which, at these low pressures, is quite inconspicuous, of course proceeds from anode to cathode, and will turn a corner without difficulty. This the cathode rays will not do. Their path is essentially rectilinear (fig. 3).

A thick, solid obstacle placed in the path of the cathode rays casts a perfectly sharp and definite shadow. The outline of the object is seen on the

wall of the vessel as a black shadow on the bright green fluorescent background (fig. 4).

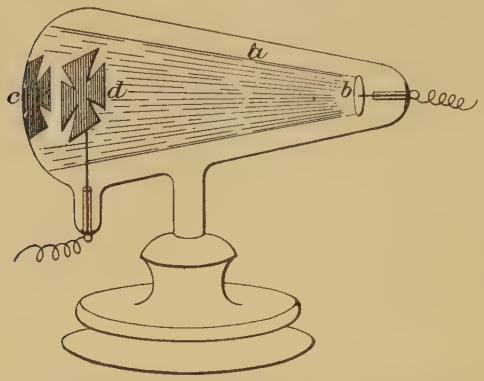

FIG. 4.—Arrangement for showing that the cathode rays are stopped by a solid obstacle, and cast a sharp shadow. A pear-shaped vessel, *a*, is used, which is highly exhausted. The plane or slightly convex cathode, *b*, sends out the rays, which cause brilliant green fluorescent luminosity on the opposite wall, *c*. The metal cross, *d*, which serves as anode, stands in the path of the rays, and casts a sharp black shadow on the luminous background.

Glass is not the only substance which becomes fluorescent under the influence of the cathode rays. Many other materials will do the same, and some of them give more brilliant effects than glass. Thus, for instance, calc spar glows with a beautiful orange-red colour. Rubies give a deep red colour, far more effective than anything that they show in the ordinary way. No rule can be given as to whether a substance may be expected to fluoresce. That can only be ascertained by trial.

The most characteristic and interesting property of the cathode rays is that they are deflected by a magnet. The deflection is very conspicuous and easy to observe. It is only necessary to bring a common horse-shoe magnet near any one of the tubes, and the luminosity of the glass will be seen to move, showing that the rays are now falling on a different spot to what they did before.

To study the effect in detail, it is desirable to have a form of tube (fig. 5) specially designed for the purpose. The cathode rays from a flat cathode have to pass through two successive diaphragms. By this means the rays are confined to an exceedingly sharp and narrow beam. They then pass through

a wide bulb, and produce a well-defined green fluorescent patch on the end wall of the bulb. The position of this patch can be read by means of a scale fastened on to the outside of the tube. Before

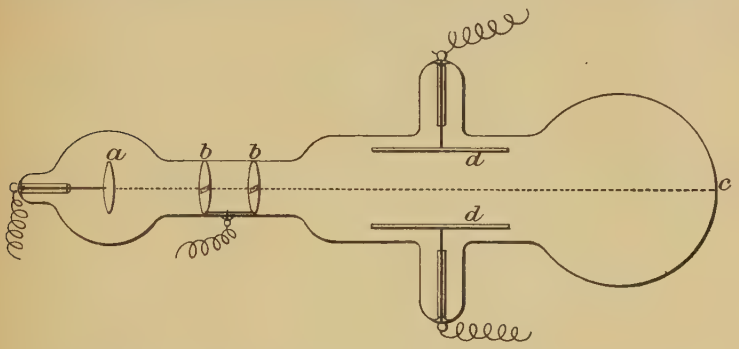

FIG. 5.—Tube for observing and measuring the magnetic and electrostatic deflection of the cathode rays. The beam of cathode rays from the flat disc, *a*, represented by the dotted line, is defined by passage through the two slits in the metal discs, *b b*. These discs are connected to the anode. The cathode rays form a well-defined fluorescent patch on the wall at *c*. They can be deflected magnetically by means of flat coils of wire carrying a current, which lie on either side of the tube, in planes parallel to the paper. Electrostatic deflection is produced by the plates *d d*, connected to the poles of a battery.

entering the bulb, the rays have to pass between two parallel metal plates, the object of which will be explained later.

In order to experiment upon the magnetic deflection, the bulb is placed between the poles of an electromagnet, or, what is better, between two coils of wire of large radius, through which an electric current can be passed. This latter arrangement allows of a very uniform magnetic field being obtained throughout the whole bulb.

When the current is turned on, so as to produce a magnetic force, the cathode rays are deflected. In other words, their path is bent into a curved form, so that they strike against the glass at a different spot. The direction in which the deflection takes place is at right angles to the magnetic force, and it can be made to change from one side to the other by reversing the current through the magnet coils, which, of course,

has the effect of exchanging the positions of the north and south magnetic poles.

To describe the direction of the deflection, we may say that if a little human figure were swimming in the cathode rays, and looking along the lines of magnetic force, he would be carried to his right.

Now, what is the most natural interpretation of this magnetic effect? We know that an electric current in a wire, if free to move, is deflected, just like the cathode rays are, by a magnetic force perpendicular to it, in a direction perpendicular to the current itself, and to the magnetic force. It is fair to conclude, at least provisionally, that the cathode rays consist of a series of electrically charged particles, fired off from the cathode. This is the explanation of the nature of the cathode rays which now obtains universal assent.

The direction of magnetic deflection clearly shows that the particles are negatively charged. Their velocity is due to the intense electric force which repels them from the cathode.

We can prove very directly that the cathode rays do carry a charge of negative electricity. For

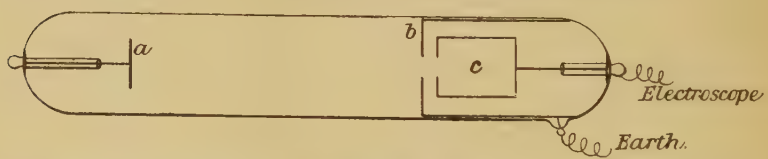

FIG. 6.—Perrin's experiment for showing that the cathode rays carry a charge of negative electricity. The rays from the flat cathode, *a*, pass through a hole in the front of the metal canister, *b*, which is earthed, and serves to protect the inner canister, *c*, from electrical disturbances. When the rays penetrate into *c*, it is found to acquire a negative charge.

this purpose the rays are made to fall into a little metal cylinder, in which their charge can accumulate. The cylinder is connected to an electroscope, and as soon as the rays are turned on, the electroscope leaves rapidly diverge with a charge of negative electricity.

If the rays are deflected by a magnet, so as to prevent their entering the cylinder, no charge is obtained. This experiment is due to M. Perrin (fig. 6).

Since the rays are charged with negative electricity, they will be repelled by a negatively charged body, and attracted by a positively charged one. The tube (fig. 5) which has been described for observing the magnetic deflection is also arranged for this experiment. The two metal plates between which the rays pass, are connected, one to the positive and the other to the negative pole of a battery of, say, 20 or 30 cells. The fluorescent patch is deflected by the electrostatic force, just as it was by the magnetic force. The rays are found to move away from the negative plate towards the positive one.

We have now to consider an important, though difficult, part of the subject. It is very desirable to get some idea of it, in order to understand what follows, when we come to discuss the properties of radio-active substances. It cannot be treated satisfactorily without making use of mathematical symbols, which would be foreign to the plan of this work. Those who can follow that kind of reasoning will find the matter set out in the simplest way that it admits of in Appendix B. For others, a verbal explanation, necessarily imperfect, must be attempted.[1]

Let us consider, then, a particle charged with electricity, and moving through a field of magnetic force. As we have seen, the moving particle, since it is equivalent to an electric current, must experience a deflecting force, which will bend it to one side. Now on what will the amount of the resulting de-

[1] If the reader finds what follows too difficult, he must be content to take it for granted that the cathode rays are negatively electrified particles of about $\frac{1}{1000}$ part of the mass of a hydrogen atom, and moving with an enormous velocity, and pass on to p. 17.

flection depend? Plainly on the distribution and strength of the magnetic force, for one thing. That can be measured experimentally, and there is nothing doubtful about it. But the deflection depends also on other things. The velocity with which the particle is moving, its mass, and the quantity of electricity it carries; of these as yet we know nothing; our object is to obtain information about them.

We have spoken as if the mass of the particle and its charge were each separately involved. But that is not exactly true. The force tending to deflect the particle depends entirely on its charge. It is, in fact, proportional to the charge. But the effect of the charge in producing sideways displacement depends on the mass to which it is attached, and which it has to drag with it. The heavier the mass with which it is clogged, the more slowly will it get up a sideways velocity, and the less it will ultimately be deflected. Increase of mass acts in the opposite way that increase of charge does. To increase this mass acts in just the same way as to decrease the charge. It is the ratio between the mass and the charge, not the actual value of either, that is essential in determining the amount of deflection.

This is so important that it will not be superfluous to give an illustration of it. Suppose instead of one single particle in the stream, we think of two of them, close together, and imagine them joined so as to make one large particle, twice as massive, and carrying twice as much electricity as the original small ones. It is quite apparent that the doubled particle will not move any differently from the single ones, although yet it carries more electricity and more matter. The absolute quantities of matter or of electricity carried by a particle are not involved.

It is the ratio between them that determines the motion.

In considering the magnetic deflection, then, there are two unknown quantities connected with each particle that are concerned. These are its velocity and the ratio of its electric charge to its mass.

The mechanical force on a charged particle moving at right angles to a magnetic field, necessarily acts in the same direction as the force which would act on a wire carrying a current under the same circumstances; that is, at right angles to its own direction and to the magnetic force. Since there is a pull on the particle at right angles to the direction it is moving, it is constrained in just the same way as is a stone tied to the end of a string, and whirled round in a circle. For the string pulls on the stone in a direction at right angles to its path, just as the force on the particle pulls it in a direction at right angles to *its* path. The particle will accordingly move in a circle, just as the stone does. The pull on the particle counteracts its centrifugal force, just as the pull on the stone counteracts *its* centrifugal force. We know, or at least we can easily calculate from observation, the radius of the circle into which the rays are bent; and we can compare their mechanical behaviour quantitatively with that of a stone whirled round in a circle of the same radius. We can calculate the pull which the string exerts on the stone, not of course absolutely, but in terms of the speed of the stone and its mass; and we can calculate in just the same way the radial pull on the cathode particle in terms of its speed and mass. The radial pull can also be expressed, however, in terms of the charge which the particle carries, its speed, and the strength of the magnetic field through which it moves. Now these two ways of computing the

radial pull, as they are both correct, must lead to the same result. We can find by expressing this a necessary relation between the speed of the particle and its mass and electric charge, which are not known, and the strength of the magnetic field and the radius of the circle in which it moves, which *are* known by direct measurement. The mass and the charge, however, only appear as a ratio, as already explained. So that we have a relation between the ratio of charge to mass on the one side, and velocity on the other. The relation is a very simple one; it is that the velocity is found by multiplying this ratio by the magnetic force and the radius. This is of course not sufficient to determine either the velocity or the ratio of charge to mass. Before that can be done, a second relation is necessary. In algebraical language, two equations are necessary to determine two unknown quantities.

The second relation can be got in more than one way. But the simplest and best is to measure the deflection of the rays by a known electro-static force.

The theory of this experiment is perhaps simpler than of that which we have been considering. The particle moves, let us say, horizontally, and the sideways electric force, at right angles to the direction of motion, pulls it down. The particle takes a certain time to travel the known length of the electro-static field. During this time it is pulled down by the electro-static field, and the distance it falls is readily deduced from the observed deflection of the phosphorescent patch. We know then how far it fell in the time. The case is exactly parallel to the fall of a rifle bullet, which makes it necessary to elevate the rifle above the

direction in which it is desired that the shot shall travel; but in our case the particle is pulled down by the electric force upon it, not by gravity. We can measure the strength and length of the electric field, and these, in combination with the deflection of the rays, give us a second relation between the velocity and the ratio of mass to charge.

We have now a pair of equations, and a pair of unknown quantities. It is accordingly a simple piece of algebra to determine what the two unknown quantities are.

The results are very astonishing. It is found that the cathode particles move with a speed not insignificant when compared with the speed of light. The speed of the rays depends on circumstances. If the pressure of gas in the vessel is not very low indeed, then a comparatively moderate electro-motive force suffices to produce discharge, and to set the cathode rays going. In this case the rays are not shot out by a very intense electric force, and consequently they move comparatively slowly, perhaps with $\frac{1}{10}$ of the speed of light. If, however, the exhaustion of the vessel is carried to an extreme point, the electro-motive force near the cathode becomes great, and the rays travel faster; speeds amounting to one-third that of light have been so obtained. The velocity of light is nearly two hundred thousand miles per second. So that the cathode particles sometimes travel at sixty thousand miles per second.

It is difficult to fully realise the meaning of such speeds as this. A shot from a modern gun leaves the muzzle at perhaps 3000 feet per second, so the cathode particle goes twenty miles while the cannon ball is going one foot! In one second the particle could go more than twice round the globe!

It is not found that the velocity of the rays is always

quite uniform in a given tube at a given pressure. For, when the fluorescent patch is deflected, it is at the same time drawn out into a band, with bright intervals separated by dark ones. This appearance is known as the magnetic spectrum of the rays. Each bright band in the spectrum corresponds to rays of one special velocity. The band most deflected from the original position is produced by the impact of the slowest cathode rays, that least deflected by the fastest. The magnetic force is thus able to sort out the fast moving particles from the slow ones.

The extended and discontinuous character of the cathode ray spectrum is due to a peculiarity of the induction coil used to produce discharge; an induction coil does not produce a steady electro-motive force. If, however, a battery of hundreds of storage cells is employed instead, the bands are not obtained. The deflected patch is no broader than the original one; the cathode rays produced are therefore all of the same velocity.

We have now to consider the other information which was got by measuring the deflection of the rays by known electric and magnetic forces—the ratio of the electric charge to the mass. Before doing so, it will be well to consider the ratio of the charge of a chemical atom, that of hydrogen, for instance, to *its* mass.

When water is decomposed by an electric current, hydrogen and oxygen are set free at the electrodes. We can measure how much electricity has passed through the water, and how much hydrogen has been set free, and it is found that the amount set free is always the same for the same quantity of electricity. It does not at all matter whether there was much water or little, or whether a large current went through for a short time, or a small current for a

long time. The amount of hydrogen set free at the electrode by a given quantity of electricity is always fixed and invariable, unless, indeed, it is absorbed at the electrode before it can get away by some chemical agency. Now the electricity is carried through the liquid by the oxygen and hydrogen atoms. Each atom concerned in the process conveys a charge of electricity. The hydrogen carries a positive charge in this case, the oxygen a negative one. The positive electrode attracts the negatively charged oxygen atom, while the negative electrode attracts the positively charged hydrogen atom.

If we find experimentally how much electricity has to pass through the liquid for one gram of hydrogen to be set free, it is evident that we have the charge carried by a gramme of hydrogen. A gramme of hydrogen no doubt contains an almost inconceivable number of atoms. But the ratio of charge to mass is the same for many atoms as for one. Thus we have learned the ratio of the charge to the mass of a hydrogen atom. It is found that the charge, measured in electro-magnetic units, is very nearly ten thousand times the mass, the mass being, of course, expressed as a fraction of a gramme.

If the cathode particles were atoms of matter, as was long believed to be the case, we should expect their mass to be at all events not smaller than this in comparison with the electric charge. For no other atom is known which has so small a mass in proportion to its charge. But, when we come to determine, in the way that has been described, the ratio of charge to mass for the cathode particles, it is found that the ratio, instead of being ten thousand to one, is about ten million to one. It cannot be doubted, therefore, that the cathode particles are something very different from atoms.

We cannot, without reference to other considerations, decide whether they are heavier or lighter than atoms. For, although the ratio of charge to mass has been determined, we do not, so far, know anything about the absolute value of either. We know that the charge is very large relative to the mass; but whether this is due to the charge being larger than the charge of an atom, or the mass being smaller, we cannot, without experiment, decide. What is wanted is a direct measurement of the mass, or, what will do as well, of the electric charge. When one of these is known, the value of the other is quite determinate.

No one has yet succeeded in inventing a way of measuring the mass of the particles; and it is not possible to measure the electric charge of the cathode particles in a vacuum tube either. But this is not the only way in which cathode rays can be produced. It is found that they are also given off by metals exposed to the action of ultra violet light; light, that is, of shorter wave-length than the eye is capable of detecting.

It would carry us too far to discuss this subject in detail, but it has been found that these particles have the same ratio of charge to mass as the cathode particles, and are beyond doubt identical with them. We owe to the ingenuity and skill of Professor J. J. Thomson a measurement of the charge which they carry.

Without entering into detail, some idea of the way in which the experiment is made should be given.

It depends fundamentally on the discovery made by Mr. C. T. R. Wilson, that the charged particles are able to act as centres of condensation for water vapour. If we have air more than saturated with water vapour, the water vapour is ready to condense

to liquid water, in the form of a fog. It cannot, however, do this unless some kind of nuclei are present for the raindrops to condense on. If there is dust in the air, the dust particles are available to act as nuclei of condensation, and there is nothing to hinder that process from freely taking place. If there is no dust, no condensation will, in an ordinary way, occur, unless indeed the air is so heavily overcharged with water vapour that condensation can occur on the molecules of air themselves.

We shall not consider such great degrees of supersaturation any further, but only those moderate degrees of super-saturation which give no condensation in the absence of dust. It is found that in this case the charged cathode particles, from metals illuminated with ultra-violet light, are able to act as centres of condensation, and to produce a fog.[1] Each particle gathers a drop of water about it, and thus there are as many drops as there are particles. We have got now, in exchange for the infinitesimal cathode particles, an equal number of drops, quite visible to the naked eye, or at all events under a very moderate magnifying power. The number of drops produced under given conditions can be estimated in various ways. The simplest way would be to let them fall on a glass plate and count them under the microscope. This was not, however, the plan adopted by Professor Thomson. He estimated the number of drops by knowing, from the conditions of the experiment, what quantity of water vapour had been condensed, and by finding the average size of each drop. This, of course, enables the number of drops to be found.

The way in which the size of the drops was found

[1] The particles require more super-saturation than dust does, to enable them to produce condensation.

is very ingenious. These drops, which, taken together, constitute a cloud, fall slowly through the air. Thus the level of the top of the cloud gradually sinks; the rate at which it sinks is observed. This is the same as the rate at which the individual drops sink. Now the rate at which a spherical drop falls through air depends on its size. For a small drop the rate of fall soon becomes uniform. The smaller the drop, the more slowly it falls,[1] and, if the rate of fall is determined, the size can be calculated, supposing, of course, the viscous resistance of the air to be known, as it is. In this way, then, the size of the drops has been found, and the number of them calculated. This is the same as the number of cathode particles. This knowledge is of no use by itself. It is essential to know also the quantity of electricity that the same number of particles carry. If we know how much electricity is carried by, say, 10,000 particles, it will not be difficult to find how much is conveyed by each.

In order to find the quantity of electricity on the particles, it is necessary to collect their charges by driving them up to a metal plate, on which their charge can accumulate and be measured. They are driven by repulsion from the metal plate from which they came in the first instance, which is negatively electrified for the purpose. If we know, as we do, the rate at which the particles move under the electric force employed, and the length of the vessel, it will be easy to find how long it will take to collect all that were present at the original moment, and none that have been added since. The quantity of electricity acquired in that time by the plate is the

[1] The case of a small drop must not, of course, be confused with the case of a heavy object like a stone. In that case the rate of fall does not depend much on the resistance of the air, and, as Galileo showed, a small stone falls at appreciably the same rate as a large one, and with accelerating velocity.

aggregate charge on the particles. As we know how many particles there are, we can find the charge on each. It is found, in this way, that each particle carries a charge equal to that carried by the hydrogen atom, as nearly as the somewhat rough estimates of the latter that we have will allow us to judge.[1]

We have come, then, to the conclusion that the charge of the particle is the same as the charge of the hydrogen atom. The charge is actually the same. Relatively to the mass, however, it is very much larger. The mass of the particle is, therefore, very much smaller than the mass of an atom of hydrogen —about a thousand times smaller.

This is a momentous conclusion, for it shows that the doctrine of the indivisibility of a chemical atom, prevalent throughout the nineteenth century, must be reconsidered. The cathode particles, or corpuscles, as they are more conveniently named, are derived from the atoms of gas in the vacuum tube, or from the electrodes, and as these corpuscles are smaller than atoms, the inference is inevitable that the atom has been split up, and that one or more corpuscles, which formed part of its original structure, have been detached from it. This consideration opens up one of the most promising lines of investigation in the entire range of physical science. We shall defer further consideration of it to a later chapter.

An important property of the cathode rays is their power of penetrating thin solid obstacles. The first observations of this kind were due to Hertz, the

[1] We have explained how the charge carried by say, 1 gramme of hydrogen atoms is deduced. In order to find the charge carried by each, it is necessary to know how many atoms there are in a gramme of hydrogen, or, what comes to the same thing, how many in a cubic centimetre. This can be calculated in various ways; but they are all rather indirect, and the results are not as concordant as might be wished. Still, the number is certain within a few times.

celebrated discoverer of electro-magnetic waves. He found that if a film of gold leaf was placed in the path of the cathode rays, they were able, notwithstanding, to produce some phosphorescence on the glass wall of the tube, though the intensity of the phosphorescence was greatly reduced by passage of the rays through the leaf.

Lenard went a step further. He arranged a small window of thin aluminium foil at the end of a vacuum tube. This window was only about $\frac{1}{35}$ inch in diameter; the object of making it so small was to support the thin leaf as far as possible against the atmospheric pressure, which tends to burst it inwards. With this arrangement (fig. 7) Lenard was able to

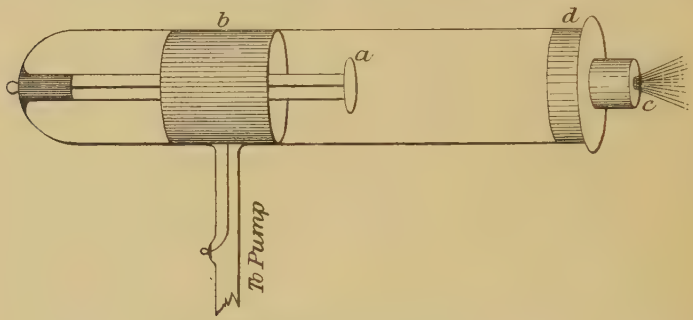

FIG. 7.—Tube for showing penetration of the cathode rays into the open. *a* is the disc-shaped cathode; a metal tube, *b*, serves as anode. Opposite the cathode is the thin aluminium window, *c*, carried by the brass cap, *d*. The rays issue from this window.

get the cathode rays through the window and out into the open air. This experiment does not succeed unless the vacuum tube is very highly exhausted, so as to obtain rays of great velocity. The rays of small velocity, obtained at higher pressures, are unable to penetrate the window. Lenard's experiments, at the time when they were first published, were considered by many to constitute a fatal objection to the corpuscular theory of the rays. It was argued that corpuscles could not penetrate a solid metal window, however thin. This is no longer felt to be a serious

difficulty, as we shall see when we come to discuss modern ideas of the constitution of matter.

The cathode rays are not able to go any considerable distance through air at atmospheric pressure. They are diffused and spread out in a fan shape from the window. If the air pressure in the space outside the tube is reduced, the rays are able to go further, but at atmospheric pressure they behave like a beam of light in a smoky atmosphere. This is due to the collision of the corpuscles with the molecules of the air. This, if it does not altogether stop them, sends them glancing off in a sideways direction.

Lenard made a series of very valuable determinations of the comparative absorption of the cathode rays by different solids and gases. The result was to show that the densest substances are the most absorbent for the cathode rays; the lightest substances are the most transparent. This rule seems to be applicable to all substances, from the densest, such as gold, to the lightest, such as hydrogen, at a high degree of rarefaction. The absorption of the rays is proportional to the density. Gold is about fifteen thousand times as dense as air; thus if the rays were partially absorbed by a piece of gold leaf it would require a layer of air fifteen thousand times as thick to absorb them as much.

Probably the law of density is only approximately true.

The transparency of different substances for the cathode rays, since it depends on density, has no connection whatever with their transparency for light. Thus, for instance, mica, which is not very different in density from aluminium, transmits the cathode rays about equally well, whereas mica is transparent to light and aluminium perfectly opaque.

The cathode rays, which have penetrated outside

the window, produce a blue glow in the air near it. This glow is of the same nature as the glow inside the tube near the negative electrode, which is most conspicuous when the pressure is not so low as in Lenard's experiments. The negative glow inside the tube is due to the passage of the cathode rays through the residual gas in the tube. If the tube is filled with air the glow shows the bands of nitrogen when examined with the spectroscope.

The cathode rays outside the tube are able to act on a photographic plate. They are also able to make the air through which they pass a conductor of electricity.

When a highly exhausted tube, in which the cathode rays are well developed, is brought near a screen of fluorescent material, such as barium platinocyanide, the screen is observed to light up, even if the vacuum tube is enveloped in black paper, and has no thin window through which the cathode rays can penetrate. This remarkable fact was observed by Rontgen in 1896, and was the origin of the discovery which has made his name famous. He soon concluded that the new rays which produced this effect, and which have been named after him, came from the place where the cathode rays impinge on a solid obstacle ; from the green fluorescent spot on the glass. It was natural to connect the Rontgen rays with this fluorescence ; but it was found a little later that the Rontgen rays were increased in quantity rather than diminished when a metal surface was arranged to receive the impact of the cathode rays. As the metal surface was not fluorescent, it is evident that fluorescence is not the essential condition for the production of Rontgen rays. The essential thing is the sudden stoppage of the cathode rays.

The form of tube which experience has shown to be the best for producing Rontgen rays is that known as the focus tube (fig. 8). A saucer-shaped

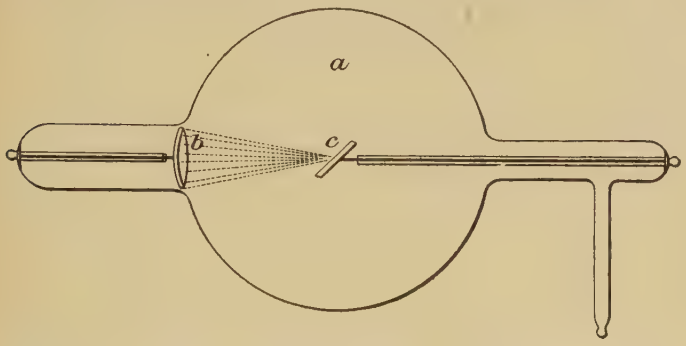

FIG. 8.—Focus bulb, *a*, for production of Rontgen rays. The cathode, *b*, is cup-shaped, and the cathode rays from it (represented by dotted lines), converge on the plate-shaped anode, *c*, inclined at 45 degrees. The Rontgen rays issue from the front of this anode.

cathode is used; since the cathode rays are shot out at right angles to the surface of the cathode, they all converge to the centre of curvature of the sphere of which the cathode forms a part. At that point a slanting platinum target is placed to receive them. Intense Rontgen rays issue from the point at which the cathode rays strike. These rays, since they issue from a single spot, are able to cast very sharp shadows.

The Rontgen rays are able to pass to some extent through all solid materials, but the facility with which they are transmitted varies very much with the material in question. The heavy metals are the most opaque, and their opacity is greater than that of light substances, such as wood or water, quite out of proportion to their extra weight. In this respect the Rontgen rays differ from the cathode rays, for, as we have seen, the absorption of the latter *is* nearly in proportion to the density. This difference of transparency for different substances is the property which enables the bones of a living

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person to be seen or photographed. The rays are able to penetrate flesh, which consists largely of water. Bones, consisting of phosphate of lime, are not nearly so transparent. The result is that, if the hand or other part of the body is placed between the tube and the fluorescent screen, the bones are seen as a deep shadow, while the flesh gives only a faint one. The rays are able to act on a photographic plate,[1] and if that is used instead of the fluorescent screen, it will record the appearance of the bone shadow permanently.

It is found that the Rontgen rays are not at all affected by a magnetic force. In this respect they differ fundamentally from the cathode rays which produced them. They are, moreover, very much more penetrating than the latter.

The view of the nature of the Rontgen rays which has gained general acceptance is that which was first put forward by Sir George Stokes. He considered that the Rontgen rays were thin pulses of electric and magnetic force, due to the sudden stoppage of the cathode particles. Electrical theory shows that the stoppage of a moving charge may be expected to produce such a pulse; the pulse would be of the same nature as ordinary light, which is now regarded as the propagation of electric waves; but with this important difference, that the length of the waves which are believed to constitute Rontgen rays would be far shorter than that of the waves which constitute visible light. We shall not, however, be much concerned with Rontgen rays in this book; and it is unnecessary to discuss further the difficult question of their origin and nature.

We have seen that the cathode rays are negatively charged particles repelled from the cathode. If the

[1] The plate is wrapped in black paper to prevent ordinary light affecting it.

right experimental conditions are attained, positive or anode rays, as they may be called, are attracted up to the cathode. If the cathode is perforated, (fig. 9) the momentum of these positive rays is

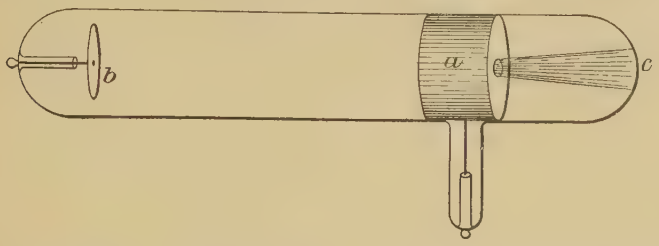


FIG. 9.—Tube for showing the canal rays. *a* is the (perforated) cathode, and *b* the anode. The canal rays issue through the hole at the back of the cathode, and cause phosphorescence on the glass at *c*.

sufficient to carry them through it. They strike on the walls of the tube, and, like the cathode rays, produce phosphorescence at the point of impact.

The positive rays are far less conspicuous than the cathode rays. They were discovered by Goldstein, long after the cathode rays were well known. He called them canal rays, in allusion to the fact that they were obtained through a channel in the cathode.

It has been found that the canal rays, like the cathode rays, are deflected by a magnet; this deflection is in the opposite direction to that of the cathode rays, and is far smaller. A magnetic form sufficient to curl up the cathode rays into a very small circle would scarcely deflect the canal rays to any measurable extent. Canal rays, too, are deflected by an electro-static field, in the opposite direction to the cathode rays.

Measurements of the deflection exactly similar to those for the cathode rays have been made by Wien for the canal rays. His experiments proved that the canal rays do not move quite so fast as the cathode rays, and that the ratio of charge to mass

is beyond measure less, being of the same value as for atoms of hydrogen, or, sometimes even smaller, as for heavier atoms. This is not the place to pursue the subject, but it will appear in the sequel that positive charges are never associated with masses of less than atomic dimensions. Negative corpuscles have alone been shown to exist, and this is probably the cause of the essential want of symmetry in the behaviour of positive and negative electricity towards matter.

In this chapter but a very small part of the subject of electric discharge has been touched on. Only those phenomena have been discussed which bear on the interpretation of the phenomena of radio-activity. We are now prepared to begin the consideration of that subject.

CHAPTER II

DISCOVERY OF RADIO-ACTIVITY

The Active Elements

THE branch of science of which this work attempts to give some account is of very recent growth. It has excited extraordinary interest to the scientific world, and has attracted a large number of workers. Thanks to their labours, the subject has advanced by leaps and bounds, and, though at the present time our knowledge is still very imperfect in many directions, we have the means of forming some idea of the meaning and cause of the mysterious phenomena which investigation has brought to light.

The first clue to the discovery of radio-activity was given by the discovery of the Rontgen rays in 1896.

We have already seen that these rays were, in the earliest experiments, observed to issue from the place where the cathode rays produced a green fluorescence or luminescence of the glass.

In the early days of the discovery it was natural to connect this greenish luminescence with the production of the rays; and the question presented itself, if we could produce the luminescence in other ways, would it give rise to Rontgen rays as in this case?

Now many substances are known which, under

the influence of blue or violet light (itself of such a quality as to be scarcely visible), are able to give out a brilliant green luminescence. Conspicuous among these are the salts of the rare metal uranium. The commonest examples of uranium salts are uranium nitrate, and potassium-uranyl sulphate. It occurred to Prof. Henri Becquerel, of Paris, to try whether these salts, when luminescent under the influence of light, would give out Rontgen rays. He exposed a photographic plate, wrapped in black paper, to the action of the luminescent salts, and found, after an exposure of some days, that a distinct impression had been produced on the plate, which appeared on development. It was natural to conclude that Rontgen rays were given off, as had been thought likely.

Extraordinary as it may seem in face of the result, this conclusion, as well as the reasoning which led to it, was quite mistaken. We now know that the fluorescence of the glass has nothing to do with the production of the Rontgen rays. We know, further, that the fluorescence of uranium salts is quite unconnected with the invisible rays which they emit. And lastly, we know that these latter are of quite a different nature from the Rontgen rays! It seems a truly extraordinary coincidence that so wonderful a discovery should result from the following up of a series of false clues. And it may well be doubted whether the history of science affords any parallel to it. For we can obtain the Rontgen rays even better by letting the cathode rays fall on a metal surface which is not fluorescent instead of a glass one which is. We can obtain invisible radiation, able to penetrate opaque substances, from uranium in the metallic form, which is not fluorescent. And

lastly, as we shall see in the sequel, these uranium rays differ altogether in their nature from Rontgen rays.

This last conclusion, however, followed much later. For most of them more easily ascertained characteristics, the uranium rays, or Becquerel rays, as they are now generally termed, in honour of their discoverer, show a striking resemblance to the Rontgen rays, and, on the other hand, a striking difference from the rays of ordinary light.

We have already noticed the action on a photographic plate, and the penetration of opaque objects. Another striking property is the absence of refraction. One of the most familiar experiments on optics is the bending of a ray of light by a glass prism; the behaviour of the Rontgen rays is very different. They are able to go straight through the prism without being turned in the smallest degree out of their original path. The same is true of the rays from uranium, though, on account of their feebleness, it is more difficult to make the experiment. If we place a little of the uranium salt at the bottom of a narrow cavity in a block of lead, so as to confine the rays into a narrow beam, we shall find that, placing a photographic plate in front of the opening a short distance away, we obtain an impression marking the point at which the rays strike the plate. If now we interpose a small prism of wood, glass, aluminium, or any other material, in the course of the beam, we shall find that the rays strike on the plate in exactly the same position as at first. The rays are not bent at all out of their original direction. This experiment is difficult with uranium, but it can now be easily repeated by making use of radium, which, as we shall see later, gives effects of the same kind as uranium but of incomparably greater power.

One of the most remarkable properties of the Rontgen rays is their power to make the air through which they pass a conductor of electricity. It must be understood that this conducting power is very much inferior to that of the metals, or even to that of acidulated water. It would not be possible, for instance, to pass an electric current through the air when made conducting by the Rontgen rays, which would be sufficiently strong to ring an electric bell, or to light an electric lamp.

The effect can readily be shown by means of a gold-leaf electroscope (fig. 10). This instrument, it will be remembered, consists of two leaves of thin gold-leaf hung side by side from an insulated support. When a charge of electricity is imparted to them, they repel one another, being similarly electrified, and, in consequence, they stand apart. The more highly charged they may be, the larger will be the divergence. If we charge such an instrument by touching it with a piece of sealing-wax which has been electrified by rubbing it on the coat-sleeve, the leaves will stand apart for a considerable time, if the air around the instrument is in its ordinary non-conducting state. But, if Rontgen rays are allowed to fall upon it, the air becomes a conductor, the charge of electricity leaks away through it, and the gold leaves fall together. The action is very apparent indeed, and cannot escape the most careless observation. I have shown

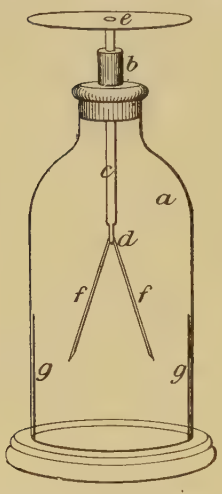


FIG. 10.—Gold leaf electroscope of the ordinary form. A bell-jar, *a*, is fitted with an ebonite stopper, *b*. Through this passes a brass rod, *c*. *c* carries at its upper end a round brass disc, *e*. At its lower end a pair of gold leaves, *f f*. *g g* are strips of tinfoil communicating with the base of the instrument, and so with the earth. When a charge of electricity is imparted to *e*, the leaves stand apart by mutual repulsion, as shown. If they diverge far enough to touch *g g*, they are discharged, and will collapse.

it at the Royal Institution with the bulb producing the rays up in the gallery of the theatre, while the electroscope, projected on a screen by means of the optical lantern, was near the table.

In the early days of the discovery of the uranium rays Becquerel obtained similar effects from them. With uranium, the collapse of the leaves is not nearly so quick as with Rontgen rays, if these are of the intensity commonly used for obtaining photographs of the bones.

Still there is no difficulty in verifying Becquerel's result. Some crystals of uranium metal may be spread on the flat disc communicating with the gold leaves with which most electroscopes are provided. It will be found that the leaves do not go down appreciably in the course of a few minutes[1] if the uranium is withdrawn to a distance. But when it is placed on the disc, the leaves lose their charge altogether in that time.

The discovery of the activity of uranium raised the question of whether any other of the seventy or more known elements possessed similar properties. It was certain that none of the materials, such as brass, copper, tin, glass, or iron, which are used in the construction of electrical instruments, could possess the power to any extent. For if they did, the leakage of electricity through the air due to their presence could not have failed to make itself apparent. It remained to make a systematic search among the less-known elements. The result was to show that one, and one only, of the elements up to that time known possessed the same power as uranium. That element was thorium. The element is rare indeed, but not so scarce as to be difficult to obtain. It is

[1] This, of course, supposes that the electroscope is in good working order.

remarkable as having the heaviest atom of any known element.

The activity of thorium is about the same as that of uranium. The discovery of its activity is due to Schmidt. Thorium is contained in the Welsbach incandescent gas mantles. Plate I. is the photographic impression produced by one of these mantles on a plate, due to its radio-activity.

Any one who has followed so far and who is familiar with the doctrine of the conservation of energy, will not fail to ask, Where does the energy come from which has enabled the uranium to affect a photographic plate and to throw the air into a conducting state? For, if there is any scientific doctrine which is thoroughly well established by experience, it is that the amount of energy in the universe remains strictly the same at all times. If the uranium gives out energy, there are only two possible sources for this. Either the uranium contains the energy stored up in itself, and is slowly exhausting its stock, or, on the other hand, it is able to draw its supplies from without and to transmute them into the form of Becquerel radiation, as the invisible radiation is called.

Becquerel was at first naturally inclined to the former supposition. The simplest explanation of the power which uranium possessed of giving out energy, was to suppose that it had stored up this energy while previously exposed to light. Such a storing up of energy is by no means outside experience. A conspicuous instance of it is in the phosphorescent substances such as calcium sulphide. This substance is familiar to every one in the form of Balmain's luminous paint, used for making match-boxes luminous so as to be easily found in a dark room.

Calcium sulphide glows in the dark after exposure to sunlight. The glow gradually becomes fainter

and fainter until it has altogether disappeared. But the substance must be left for a considerable time in the dark before this happens. Exposure to light revives the luminosity again. It was thought, then, that the behaviour of uranium might be analogous to this. But experiment did not confirm the idea. For it was found that uranium salts which had just been exposed to the sunshine were exactly equal in photographic power to those which had been long kept in the dark. Indeed, it was found that if the uranium nitrate was actually exposed to sunshine while it was acting on the plate (the latter of course wrapped in black paper), there was no increase in effect. An even more crucial test might be made with some mineral containing uranium. If a piece of such a mineral were broken in half in the dark, and the activity of the freshly exposed surfaces was tested, it would be found that it was absolutely normal. It is evident that the material constituting these surfaces has never seen the light since the formation of the mineral, which, there can be no doubt, occurred countless ages before the appearance of man on the globe. So that the experiment would show conclusively that previous exposure to light had nothing to do with the matter. I am not aware that the experiment has been made in this form, but there can be no doubt of what the result would be, in the light of our present knowledge.

Another suggestion which was made as to the source from which uranium got its energy, was that it was able to draw energy from the surrounding air. According to the kinetic theory of gases, air consists of a number of minute particles called molecules, which produce pressure on the walls of the containing vessel by their constant impacts with it. These molecules are believed to be flying about with

varying velocities, some below the general average, others above. But the mean velocity[1] about which the actual velocities fluctuate, depends on the temperature, and is fixed so long as the temperature remains steady. At the freezing point it is, in the case of air, more than a thousand feet per second.

Now the molecules moving with a velocity above the mean, would, if they could be separated from the rest, have a greater mean velocity than these. Consequently these fast molecules would constitute a hotter portion of air, and the others a colder one, than the original air. Can such a separation be practically effected? All previous experience goes to show that it cannot without calling in the aid of other external sources of energy. Is it possible that in uranium we have at last been able to find an agent for utilising the energy which exists in the heat of the surroundings, without making use of any pre-existing difference of temperature? It certainly cannot be said to be *à priori* an impossibility, for we can give no proof that energy cannot be made available in this way. All we can say is that human experience has failed up till now to furnish any case of such a thing being done.[2]

Attractive though this suggestion may seem, there are insuperable objections to it. When we come to deal with radium, an experiment will be described which conclusively shows that radio-active bodies do not acquire their energy in any such way. In

[1] In strictness it is the velocity of mean square that is concerned. To compute it, we take the square of the velocities, average them, and take the square root of the result.

[2] An article appeared in a popular magazine a few years ago, describing a process of obtaining liquid air, and using it to obtain more liquid air, with a surplus of power remaining over. It excited a good deal of enthusiasm among the unscientific public. If this were really feasible it would be a case in point. But those who had any knowledge of the theory of heat ventured to doubt whether it had been done as asserted; and the result has justified their scepticism.

the meantime we may note that if the air was the source of energy, it might be expected that the radio-activity would be reduced by placing the substance in an exhausted vessel. Such, however, is not found to be the case.

We are, then, reduced to assume, either that the uranium is acquiring its energy from some external source by a process of which we can form no conception, or that it is giving off potential energy of its own which it had possessed all along, undergoing, of course, some change in the process.

It may be asked, if this latter assumption is to be considered, How is it that the change of other qualities which must accompany this loss of energy does not become visible? How, in fact, can uranium remain uranium? The answer must be that it does not—that if we could only watch it for a sufficient time, the change in its qualities, when it had given off its energy, would become apparent. The rate of emission of energy is so small when compared with the total stock that the uranium possesses, that, during the hundred years or so that the metal has been known, the changes proceeding in it have not visibly altered its properties. This is the view now generally held, and we shall see in later chapters that there is very strong evidence in support of it.

It has been explained how the wonderful radiating properties of uranium were discovered. We now come to the more sensational developments which have attracted so much attention of late.

It is found that all the compounds of uranium emit Becquerel rays. They are all able to affect a photographic plate which has been wrapped in black paper, and they can all discharge a gold-leaf electroscope. It was a natural and obvious experiment to compare the various compounds of uranium amongst them-

selves, in order to see which was the most active. The experiment is not difficult. It is merely necessary to place equal quantities of the various compounds successively on the plate of the gold-leaf electroscope, and to compare the times which the leaves take to collapse in each case.

For this kind of work a special form of electroscope has been devised, which is very convenient. The leaf of the electroscope can be observed by means of a microscope with a scale in the eye-piece, which is focussed on it. Thus the rate at which the leaf goes

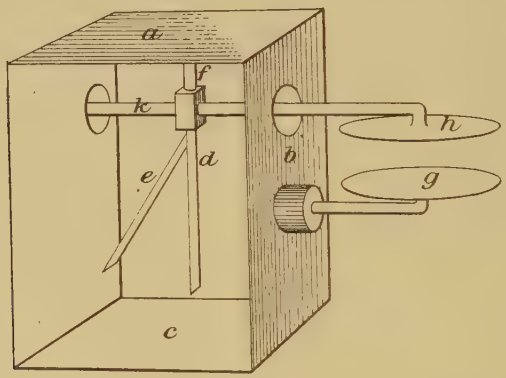


FIG. 11.—Electroscope designed by M. Curie for measurements in radio-activity. The instrument is enclosed in a brass case, *a b c*. The front wall is of clear glass, the back one of obscured glass, to provide a diffused light. A metal strip, *d*, hangs by an insulating support, *f*, from the roof. To this strip the gold leaf, *e*, is attached. A metal plate, *h*, is connected to *d* by a brass rod, which passes, without touching, through a hole in the case. A second metal plate, *g*, is in metallic communication with the case. On this the radio-active substance is spread, and causes a leak of electricity from the electrified plate, *h*. The leaf thus gradually collapses. The rate of motion is read by means of a microscope with scale in the eyepiece, focussed on the leaf. For charging the instrument, a knob (not shown) is provided, which projects outside the case, carried by the rod, *k*. This knob, also the plates *h*, *g*, are provided with metal covers to screen them from external influence.

down can be read. A metal plate is provided to carry the radio-active substance (fig. 11).

Comparisons of the uranium salts were carried out by Madame Curie. She found that the various compounds did not differ much among themselves in activity. The compound of uranium with oxygen,

for instance, known as uranium oxide, discharged the electricity about as fast as the compound with nitric acid, uranium nitrate. There were slight differences, attributable to the fact that some of the compounds contain a larger percentage of the metal than others. But these differences were comparatively unimportant. The essential thing was, apparently, the presence of uranium. What other element it might be combined with did not matter much. Indeed, an ingot of the metal itself gave a result not very different from the compounds.

THE DISCOVERY OF RADIUM

Uranium, like most other metals, is obtained from an ore which is quarried, or mined, out of the earth. This ore is called pitchblende. It is not a very common mineral. When it does occur, it is usually found among igneous rocks, like granite or felspar (Plate II). It is very valuable, as it consists mainly of uranium oxide, which is in demand for making canary glass.

Madame Curie turned her attention to this substance, to see whether it behaved like the artificial compounds of uranium. To her surprise she found that it was very much more powerful than any of them. One specimen of pitchblende, for instance, which had come from Joachimsthal in Bohemia, was three or four times more active than uranium.

What could be the explanation of this? Why should the native compound of uranium be so much more energetic than the artificial purified product? Madame Curie's answer was that pitchblende contained, besides uranium, some new substance which was far more radio-active.

It has been mentioned that pitchblende consists mainly of uranium oxide. But in addition to this it

contains small quantities of many metals, such as iron, copper, lead, bismuth, and others. Indeed, there are probably few metals which would not be found in it, if the search were carried out with sufficient care. The problem of separating pitchblende into all its constituent parts is, accordingly, very complex. The methods of chemical analysis, however, make it possible to effect the separation.

Monsieur and Madame Curie proceeded to do this, and they tested at every stage the radio-activity of the products, using the gold-leaf electroscope as before.

It will not be necessary to enter into the details of this process of separation, but some general idea of it may be given. In the first place, the mineral is heated with a suitable flux, and then dissolved in hydrochloric acid. The solution is treated with the gas known as sulphuretted hydrogen, a compound of hydrogen and sulphur, which possesses the smell characteristic of rotten eggs. A black mud, or precipitate, is immediately thrown down from the clear solution. This is separated from the solution by filtering. It is then dried, and tested with the electroscope. It is found to be radio-active, and, on further separating it into its constituents, which include, amongst others, copper, bismuth, and lead, the radio-activity is found to accompany the metal bismuth.

The clear solution from which the black precipitate was separated is now free from the metals which the precipitate contained. Ammonia is added to it, and a new precipitate is formed. This precipitate contains iron, uranium, and other elements, and is, of course, also radio-active, owing to the presence of uranium.

Separating the clear liquid by filtration, as before,

we add ammonium sulphide, a reagent prepared by passing a stream of sulphuretted hydrogen into ammonia. This separates a further precipitate, which is not appreciably active.

The clear liquid, or filtrate, as it is called, which is left after this operation is treated with carbonate of ammonia, often known as sal volatile. This time a precipitate is obtained which is far more active than the original pitchblende. The principal active constituent has at last been run to earth. The precipitate obtained by adding carbonate of ammonia contains those metals which are called metals of the alkaline earths. Calcium, which is the metallic constituent of chalk and lime, is the most abundantly distributed of these. Lime is the compound of calcium and oxygen, just as rust is the compound of iron and oxygen. It is, in fact, the rust of calcium.

Another alkaline earth metal is known as barium. This is much less common than calcium, but still fairly abundant, and it is this metal which is chiefly present in the precipitate which the solution of pitchblende gave when treated with carbonate of ammonia.

Is it, then, to be concluded that barium is radioactive? The answer must be in the negative, for it is found that barium extracted from other minerals, such as barytes or heavy spar, is not at all so. It is evident that the barium from pitchblende contains some other substance, which is so like it in chemical properties that all the chemical operations which the material has undergone have failed to separate them.

There is a method which hardly ever fails to separate two metals, however closely they may resemble one another, and that is the method of fractional crystallisation. To explain this method a slight digression will be necessary. Suppose that we have

a salt of barium, barium chloride for instance, and dissolve it in water. It will be found that the amount that will dissolve at the ordinary temperature is limited and definite. But, if the water is heated to the boiling point, we can dissolve much more. If we dissolve as much as we can in boiling water, and then let the clear solution cool down, what will happen? The solution cannot, when cold, hold so much salt as it did when hot, and so some of the salt will separate out in crystals on cooling. Suppose, now, that we have a mixture containing both barium chloride and calcium chloride. We dissolve this in water, adding enough water to dissolve the whole of it. We then heat the water to boiling, and boil it away until salt just begins to separate out from the boiling solution. Then we let it cool. Part of the salt separates out; but, since barium chloride is less soluble than calcium chloride, it is more ready to separate from the solution. So the separated salt contains more, and the solution contains less, of the barium chloride than the original salt did. One step has been taken towards separation. Next we collect the separated salt, dissolve it in water, and treat the solution exactly as before. This time the salt which separates is still richer in barium chloride, and, if we go on long enough, we shall, in the end, be able to obtain the barium chloride quite free from calcium chloride. The process is slow, but sure.

This example illustrates the process which M. and Mme. Curie applied to the radio-active barium which they had obtained from pitchblende. They converted it into the chloride, dissolved it in water, and boiled the water until crystallisation commenced. Then they allowed it to cool, and collected the separated crystals. These crystals when dried were found to be more active than the material from which the solution had

been made. The material still in solution when recovered was, of course, less active. It was evident, therefore, that associated with the barium chloride there was a radio-active metal, allied to barium, which formed a chloride less soluble than barium chloride. It had been partially separated from the barium chloride, just as, in the example we gave, barium chloride was separated from calcium chloride. This new element was named Radium, in allusion to its radio-active properties.

By working on large quantities of material, and by repeated fractional crystallisations, M. and Mme. Curie obtained products more and more active. At every crystallisation the activity became greater, and at first it seemed as if there was no limit. It will be understood that, starting with a small quantity of the mixture, the amount becomes less at every operation, until, after a certain number of crystallisations, the amount remaining becomes too small for further treatment. The only escape from this difficulty is to take very large quantities of the mineral to begin with. Pitchblende is a valuable mineral, as we have seen, because of the uranium contained in it. But the residues left after the uranium had been extracted were worth little or nothing, and could be had for the asking, though that is no longer the case. These residues contained all, or nearly all, the barium and radium, and several tons of this material were worked up by M. and Mme. Curie. Now that the properties of the material sought for were known, it was no longer necessary to separate every constituent in the mineral. It was merely necessary to obtain the barium with its accompanying radium. For this purpose a process which was simpler and more direct than that which we have followed was devised (see Appendix C). It will be unnecessary to follow this in detail; suffice

it to say that many pounds of the barium chloride containing radium were obtained. The mixture was systematically treated by fractional crystallisation. At every step stronger and stronger products were obtained. After several operations a product no less than thirty times more active than uranium was obtained. Surely at last the product, if not pure, must at least contain a large proportion of the new element? A piece of platinum wire was dipped in the salt, and then into the blue non-luminous flame of a bunsen gas burner. The characteristic green coloration produced by salts of barium was visible, and when the light was analysed by means of a prism, the only rays which were at all conspicuous in the spectrum were those produced by barium salts. But, on closer examination, faint traces of new lines were visible. These were attributed to the new element, but it was evident that, even in this intensely active product, the proportion of the new element was small. It was necessary to persist with the fractional crystallisation. The products became more and more powerful, until at last, when the salt was examined in a bunsen flame, the green colour due to barium began to become less conspicuous, and the red rays characteristic of the new substance began to be predominant. Finally, when the quantity of salt had been reduced to the merest pinch, by the successive reductions at each separation, the barium rays could no longer be seen. Pure radium chloride had at last been isolated, at the expense of almost incredible labour and perseverance. The activity of the product so obtained was truly amazing. It discharged the electroscope a million times faster than uranium. It would almost instantly fog a photographic plate brought near it. Sir William Huggins has mentioned a striking example of its power in this respect. Five milli-

grammes of the salt, which would, perhaps, be about the size of a grain of corn, were put in the top drawer of an ordinary writing-table. A packet of photographic plates happened to be in the bottom drawer of the same table. These were required for use a few days later; but it was found that they had been completely fogged by the radium, which was, probably, eighteen inches off, and separated from them by the contents of the intervening drawers!

Different samples of pitchblende vary very much in the quantity of radium that they contain. English pitchblende, from Cornwall, contains much less than the Joachimsthal ore used by M. and Mme. Curie.

Pitchblende is the only source from which radium has yet been extracted in the pure state. It is, however, by no means the only mineral which contains the element. Most of those minerals which contain uranium, thorium, and the rare earth metals, cerium, yttrium, etc., contain traces of radium also (see Appendix D). Examples of these are samarskite, a black, heavy, lustrous mineral, which contains the oxides of many metals, including niobium, tantalum, and yttrium; fergusonite, another black mineral from felspar rocks in Sweden; and cleveite, a substance allied in its nature to pitchblende, and interesting on account of the fact that it was the first discovered source of terrestrial helium. All these substances are of very rare occurrence, and the proportion of radium contained in them is even smaller than in good pitchblende.

Radium occurs also in certain mineral waters, notably in those of Bath and Buxton. But the proportion is very small indeed. Nor indeed could it be otherwise; for these waters all contain sulphates of lime and other metals in solution. These sulphates would precipitate almost all the radium that might

be in solution in the form of radium sulphate. No saline substance that we know of is absolutely insoluble. But the sulphate of barium only dissolves very sparingly. And in all probability the sulphate of radium, the next in the series of alkaline earth metals, is very much less soluble still. It is interesting to note in passing that the proportion of barium sulphate in a saturated solution is about fifty times as great as the proportion of radium in pitchblende. And it is usual to regard barium sulphate, for the ordinary purposes of chemistry, as absolutely insoluble!

I have found that the iron deposit left by the Bath water contains much more radium than the salt obtained by evaporating the water. It contains as much, in fact, as some of the less active minerals. The same is true of the Buxton deposit. But the annual yield of deposit by the springs is very small in both cases.

It would be very interesting to know whether the medicinal value of these mineral waters is connected with the presence of radium in them. Some of the waters which have great repute are so nearly pure that their virtue has always been regarded as very mysterious. There does not seem to be any sufficient peculiarity revealed by the analysis of the water to explain why it should be better than any ordinary spring water. If this could be traced to the presence of radium, the mystery would be in great measure explained. For the presence of even a very small proportion of a substance so energetic might be expected to produce remarkable results.

Comparatively few waters have been examined as yet. But the subject is 'in the air,' and, no doubt, large additions to our knowledge will soon be made.

Many kinds of soil and rock also contain traces of radium. But these traces are very slight indeed, and can only be detected by special methods. The element, rare as it is, is none the less distributed in recognisable traces almost everywhere.

The question is often asked, Is there any probability that radium will ever be found in large quantities?

It would be rash to make any confident assertion on the subject. It must be admitted that several elements, which at the time of their discovery were very rare, have turned out to be in reality relatively abundant. Thorium and vanadium are examples of this. Thorium, for instance, was originally found in the rare Norwegian mineral thorite. Berzelius, who was the first to investigate the properties of the element, was only able to obtain enough material to furnish him with a few grammes of it. But now it has been found in large quantities in the mineral monazite in Brazil, and is worked up commercially by the ton for use in preparing the mantles of incandescent gas lamps.

We cannot feel sure, therefore, that because the supplies of a new element are scanty at first, they necessarily remain permanently so. But in the case of radium the prospects of obtaining large quantities do not seem to be very encouraging. The presence of radium in a mineral, even one part in one hundred million, can be detected in one or two minutes by the electrical test. So that it is far more easily searched for than other elements, which require the application of tedious chemical processes to determine their presence or absence. Accordingly the search for radium has been carried out very thoroughly. And the result has been to make it certain that it is indeed very much rarer than any other known

element, with the possible exception of the rare gases, helium, neon, krypton, and xenon.

It is not beyond the bounds of possibility that a mineral may be found which contains radium as a principal constituent. But it does not seem likely that such a mineral is to be found in any of the very extensive collections which exist. Such collections have been examined, and the radio-activity of promising minerals has been tested with the electroscope. But nothing more active than pitchblende has been found. Indeed, if any mineral containing a considerable percentage of radium existed in such a collection it would not have escaped notice. For the glass of the show-case containing it would have been coloured a deep violet by the Becquerel rays.

There are no doubt large portions of the earth's surface of which the mineral constituents have not been minutely examined. It is by no means improbable that a richer variety of pitchblende than any yet known may be found in such imperfectly explored regions. It is even possible that a mineral may be found which contains radium as a principal constituent. These are, so far as can be seen at present, the only ways in which the element can become appreciably easier to procure than it is now.[1]

POLONIUM

It was mentioned, in describing the analysis of pitchblende for radio-active substances, that the precipitate formed by sulphuretted hydrogen in acid solutions is radio-active. This activity is found on further analysis of the precipitate to be mainly associated with the bismuth contained in it.

[1] In the light of the most recent investigation, it seems probable that the radium in a mineral bears a fixed and very small ratio to the uranium. If that is so, all hope of obtaining radium in quantity must be abandoned.

Bismuth is present to a considerable extent in the pitchblende. Ordinary bismuth is quite without radio-activity, so that it is clear that the radio-activity is not due essentially to the bismuth itself, but to some radio-active substance contained in it, which is very similar in its chemical behaviour. This new substance has been named by Mme. Curie, polonium, in honour of her native country.

It is very doubtful whether polonium has been isolated in a pure state. The separation from the accompanying bismuth was found by Mme. Curie very much more difficult than the separation of radium from barium.

The methods employed by her were very similar in principle to those used for the latter separation. They depended, however, on fractional precipitation instead of fractional crystallisation. Polonium-bismuth was dissolved in nitric acid, and water added to the solution. This process partially precipitated the material in the form of a basic salt, which was found to be much richer in the active constituent than the original substance had been. The process was repeated many times, and eventually a very concentrated product obtained, which possessed intense radio-activity. It was not found, however, to exhibit any characteristic spectrum distinct from that of bismuth.

The fractionation was very difficult to carry to great lengths, for insoluble compounds were formed which could only be got into solution by the tedious process of first reducing them to the metallic form by fusion with potassium cyanide. Attempts to fractionate the radio-active bismuth by other methods met with no better success. The most active products which could be got still evidently consisted for the most part of pure bismuth.

More recently Professor Marckwald has discovered a far more simple and effective method of separation. He does not make use of sulphuretted hydrogen in separating the bismuth from the original pitchblende, but precipitates it with water from a hydrochloric acid solution of the mineral. The bismuth is dissolved up afresh in hydrochloric acid, and a rod or plate of metallic bismuth immersed in it. The result is that the radio-active material is wholly deposited on the immersed metal in the course of a few days. None at all remains in the solution.

This process of separation is quite analogous to many other familiar ones. For instance, if an iron knife is placed in a dilute solution of copper sulphate, the copper will all be deposited upon it, while some of the iron will go into solution and will replace the copper in its combination with sulphuric acid.

It is found that copper as well as bismuth may be used for the deposition of polonium.

The amount of deposit obtained is exceedingly minute, but of very high activity, sufficient to produce conspicuous phosphorescent effects, such as will be described in the next chapter. But even so, it does not consist wholly, or even mainly, of polonium ; the principal constituent is tellurium, a rare element which occurs in pitchblende in minute traces. The tellurium can be precipitated from a solution of the deposit by means of hydrazin-hydrate, and polonium, presumably in a pure state, remains in solution. Only four milligrammes were obtainable from two tons of pitchblende, so that the proportion present is only one part in five hundred million.

The activity of the product is so great that an electric current can be sent through the air in its neighbourhood sufficiently strong to ring an electric bell.

It is right to state that Professor Marckwald does not regard the product obtained by him as identical with Mme. Curie's polonium. But his reasons for considering it different are not, so far as the author is aware, generally regarded by current scientific opinion as having much weight.

The nature of polonium is a somewhat obscure subject. It is certain that it diminishes in activity as time goes on, and some have for that reason regarded it as being a form of bismuth made active by the neighbourhood of radium, rather than a true radio-active element. But in the light of recent investigation this objection has lost its cogency, as we shall see in a later chapter.

Polonium appears to lose half its activity in the course of about nine months. But this subject requires further and more minute investigation than it has yet received. Mme. Curie has recorded that in some specimens of polonium the activity disappears more quickly than in others. If this should be confirmed, the most probable explanation would seem to be that two substances are present whose activity decays at different rates. If these are present in varying proportions, the aggregate effect might decay at any intermediate rate.

The quantities of polonium hitherto prepared have been too small to allow of a determination of its atomic weight. Its general chemical behaviour is very closely analogous to that of bismuth. Whether other minerals besides pitchblende contain it has not yet been ascertained.

ACTINIUM

Subsequently to the original investigation of M. and Mme. Curie on pitchblende, which lead to the discovery of radium and polonium, M. Debierne was

able to establish the presence of a third new radio-active element, to which he gave the name actinium. This substance is nearly allied to thorium in its chemical behaviour. It is precipitated, along with uranium and many other metals, in the ammonia group, in the process of analytical separation of the constituents of pitchblende. But for preparing it in practice, the waste residue, free from uranium, is used.[1] M. Debierne has mentioned several reactions which may be used for separating a product rich in actinium from the mixture of other metals in the ammonia precipitate. One of these is to dissolve the precipitate in weak hydrofluoric acid; it is found the actinium remains in the least soluble portion. An alternative method is to add some soluble barium salt to a solution containing actinium, and then to precipitate the barium again by means of sulphuric acid. The sulphate of barium carries down the actinium with it. This procedure is recommended as being specially effective.

Much less is known of actinium than of radium and polonium; doubtless because the material is very scarce indeed, and because the chemical separations necessary for preparing it are difficult to carry out, actinium has not yet become obtainable commercially.

Pure actinium has not been obtained. Even the strongest products containing it consist mainly of thorium. Thus we have no information as to its atomic weight. Nor has it been observed to yield a characteristic spectrum.

In addition to the radio-active elements which have been discussed, and whose existence is well established, a radio-active substance associated with the lead of pitchblende has been described. Sufficient evidence has scarcely yet been accumulated to deter-

[1] See Appendix C.

mine whether this is a genuine radio-active element, or whether it is only made active by traces of radium, or by having been in the same solution with radio-active elements.

To sum up, the well-established radio-active elements are :

Uranium.
Thorium.
Radium.
Actinium.

Polonium is less certainly a genuine element, though the balance of evidence now seems to be in favour of the view that it is one. Radio-active lead is very doubtful.

The first three only have been obtained in weighable quantities in the pure state.

CHAPTER III

THE PROPERTIES AND NATURE OF THE RADIATIONS

In the foregoing chapters we have, in the main, followed the historical order of development of our subject. But, in pursuing it further, it will be more convenient to abandon this plan. The number of workers in the field of radio-activity has been very large, and will probably increase still more, as the supreme importance of the subject, and the chance which it seems to give of far-reaching discoveries, comes to be recognised. The work of different investigators is so interwoven, and so many have assisted in the development of particular points, that it would lead to hopeless confusion if an attempt were made to present the subject in the order in which it has been actually unfolded.

A question which cannot have failed to present itself to every reader of the foregoing pages is this: What is the nature of the mysterious influence which is emitted from radio-active bodies, which can penetrate, which can affect photographic plates, and can discharge electricity, even after passing through solid metal screens?

Before coming to this, we shall describe some further experiments with the rays. We shall begin with some which show that, whatever the Becquerel rays may be, they are not all of the same kind.

Suppose we take a very small quantity of radium salt and place it on the lower plate of the electro-

scope (fig. 11), the rate of discharge will be extremely rapid. If the leaf is given a charge of electricity, it will lose it almost immediately, owing to the discharging power of the radium. But if we place one sheet of common tinfoil over the radium, and try again, we shall find that the charge is lost, quickly, indeed, but still very much less so than before. Perhaps the rate of discharge will now be only one-tenth as great as it was at first. Let us next put on a second sheet. What is the rate of discharge to be now? Will the second sheet reduce it tenfold again, like the first? By no means. We find that the second sheet produces very little effect. It is evident that the rays which are able to get through a sheet of tinfoil are of quite a different kind from the bulk of those given out by a bare radium salt. The sheet of foil has acted like a filter. It has filtered out and stopped an easily absorbed kind of rays, and it has allowed another kind of rays, which are more penetrating than the first, to get through. These penetrating rays are not appreciably absorbed by a sheet of this thickness, and consequently the insertion of the second sheet does not affect them materially.

It may be asked, Are the rays which survive the first and second sheet of tinfoil all of the same kind, or do they include a third kind, even more penetrating? Experiment shows that they do. If we place a block of lead a quarter of an inch thick on the radium, we shall find a great reduction of discharging power. It may now take some minutes for the motion of the gold leaves past the divisions of the scale to become apparent. If we add another such block, the motion of the leaves will, indeed, be slower still, but not very markedly so. The second kind of rays have been filtered out, and a third kind, still more penetrating, has been left.

The first kind of rays, those which are stopped by very thin screens, have become known as the α-rays. The second kind as the β-rays, and the third kind, the most penetrating of all, the γ-rays.

There are certain properties common to all three kinds of rays. They can all produce electric discharge, as we have seen; and they can all act on the photographic plate. These are the methods which are generally most convenient for the detection of the rays.

FLUORESCENCE PRODUCED BY THE RAYS

Another striking property which the rays possess is that of causing fluorescence; that is, they can cause certain substances to glow with a luminosity easily visible in the dark, but unaccompanied by appreciable rise of temperature. The diamond is one of the most conspicuously fluorescent substances. The experiment is very easy. It is merely necessary to go into a dark room provided with a small quantity of radium bromide, and to bring it near a diamond ornament. The stones at once glow with a bluish light. If the ornament includes other stones, such as rubies, these will appear quite black. A ring consisting of rubies and diamonds alternately shows this very effectively. The diamonds shine out brilliantly, while the spaces between them, filled by the rubies, are dark.

This fluorescence of diamonds forms a very convenient test of their genuineness, quite within the reach of any one who can obtain the use of a little radium. For imitation diamonds do not fluoresce, or at least so slightly compared with the real ones, that there is no possibility of mistaking them. In this simple way real diamonds can be distinguished from false ones, without any expert knowledge whatever.

Other substances which are brilliantly fluorescent are zinc sulphide, which glows most brilliantly under the α-rays, and barium platino-cyanide, which is best for the β- and γ-rays.

Screens are made of these substances spread on cardboard, which are very convenient for experimental purposes. The platino-cyanide screens sold for showing the bones of the hand with the Rontgen rays, are also suitable for observations with radium. If a small quantity of radium be brought up to such a screen, it will be seen to be faintly luminous with the rays falling on it. On bringing the radium nearer, the luminosity becomes stronger, but is of course spread over a smaller area. The luminosity is nearly as bright if the radium is brought up on the blank side of the screen, since the rays can easily penetrate the cardboard, and excite the luminosity of the prepared surface. The luminosity will still be seen if a piece of metal is inserted in the path of the rays, before they fall on the screen. If the hand be placed against the back of the screen, and the radium held some inches off, the shadow of the fingers will be seen on the screen, and it may even be possible to make out something of the bones. The difference between flesh and bone is not nearly so clear, however, as with Rontgen rays. We shall return to this point later.

An interesting example of fluorescence under Becquerel rays is afforded by the tissues of the eye itself. The effect is easily observed. Close the eye, and cover it with black paper, so as to exclude all light from without. Now bring up the radium outside. Distinct luminosity will be perceived, owing to the fluorescence of the tissues under the Becquerel rays, which penetrated the paper and the closed eyelid.

The fluorescence is naturally most intense when the fluorescent substance is very close to the radium. The most brilliant effects of all are obtained by mixing them. If some zinc sulphide is mixed with radium bromide, and any design painted on a card-board screen, it will glow perpetually in the dark.

It is natural to inquire whether there are any means of foreseeing whether a substance will be fluorescent under the Becquerel rays, or not. There are no means by which we can be sure, for the reason why some substances fluoresce, and others do not, is quite obscure. There seems to be a connection between fluorescence under Becquerel rays and fluorescence under the action of light. Many of the substances which fluoresce under one agent, also fluoresce under the other. Barium platino-cyanide is a conspicuous example of such coincidence. But the rule is far from universal. Some of the aniline dyes are very fluorescent under the action of blue or violet light, lighting up with a brilliant green colour. But they remain quite dark in the neighbourhood of radium. Again, the majority of diamonds do not fluoresce much under the action of light, while they all appear to do so to some extent under the Becquerel rays.

In some cases, luminosity produced by the Becquerel rays persists after the rays have ceased to act. It is said that some varieties of fluor-spar will remain feebly luminous for days after they have been exposed to radium.

CHEMICAL EFFECTS OF THE RAYS

One case of chemical action induced by the Becquerel rays has already been encountered. That is their action on photographic plate. The bromide of silver contained in the gelatine film is reduced to a

lower state of oxidation, or rather bromination, and this renders it susceptible to further reduction to metallic silver by the developer. The action is, so far as we know, identical with that produced by ordinary light on the plate.

Many chemical changes are set going by the neighbourhood of radium.

For example, if a radium salt is dissolved in water, the water is continuously, though very slowly, decomposed into its elementary constituents, oxygen and hydrogen. The mixture of gases is slowly evolved in minute bubbles.

The Becquerel rays are able to change the yellow inflammable kind of phosphorous into the red inert variety.

The fluorescence of barium platino-cyanide under the rays has been noticed. This substance is ordinarily lemon-yellow in colour, and very fluorescent. But if it is kept near the radium for many hours, it will become changed into an orange-red compound, which is not fluorescent at all.

Another example of the same kind is the coloration of glass by the rays. If a radium salt is kept for a few days in a glass bottle, the glass will be seen to have become distinctly violet. With prolonged exposure to the rays the coloration becomes very deep. The exact nature of the change here occurring is not certain, but it is generally believed that the violet colour is due to the separation of alkali metal (sodium or potassium) in a finely divided state. The glass of a Rontgen tube becomes coloured in the same way after long use, though not nearly so strongly.

Most salts of the alkali and alkalium earth metals acquire colour under the influence of the rays. Common rock-salt becomes blue. Barium salts containing radium, such as are obtained in the early

stages of preparation of the latter, become red under the influence of their own rays.

In all cases the colour disappears when the substance is dissolved in water; and by subsequent drying, a white salt is again obtained.

The violet colour of the glass is destroyed by heat.

One other example of a chemical action set up by the rays may be described—not because it is in itself specially interesting theoretically, but because it has been found very convenient as a practical means of detecting the presence of the rays.

It has been found by Mr. Hardy and Miss Wilcox that a solution of iodoform in chloroform turns violet under the action of light. This violet colour is due to the liberation of iodine. A little oxygen is necessary for the reaction to take place; but the atmosphere supplies this.

If no light is acting, the solution remains colourless. But in sunlight the violet colour soon becomes conspicuous. The exact nature of the change is not known. The interesting point is that the Becquerel rays are able to set it going, as well as light.

This reaction can be observed, even if the radium is covered by thick lead, though, of course, under such conditions it is very slow. The β- and γ-rays are concerned in producing it. The α-rays do not appear to have much effect, if any.

In most of the cases which have been described, the question of which kind of rays is chiefly operative in producing chemical action has not received much attention. But probably the β-rays are usually most concerned. It is certainly so in the case of the action on a photographic plate; for in this instance the α-rays have comparatively very little effect.

The examples which have been given by no means exhaust the list of chemical actions which are promoted

by the Becquerel rays. Indeed, it is perhaps not too much to say that they will be found to exert an influence on the majority of chemical actions. The subject offers a very wide field for experiment, and one which has as yet hardly been touched upon. It is very possible that the action of the rays may be found in some cases to result in the formation of new compounds, which cannot be produced in any other way.

The effects of fluorescence and chemical action which we have been describing cannot, for the most part, be detected with the feeble radiation of uranium. It is necessary to make use of the much more powerful rays of radium in order to observe them.

PHYSIOLOGICAL PROPERTIES OF THE RAYS

For the sake of completeness, it is necessary to say a few words about the physiological effects of radium ; these may ultimately prove to be of the utmost importance from the standpoint of practical medicine.

The effects were first brought to light in a somewhat dramatic way. M. Becquerel had for some time carried in his waistcoat-pocket a small sealed tube containing a radium preparation, in order to have it ready to show to his friends. After a short time, the skin underneath the pocket became red and inflamed. Eventually it developed into a painful sore, which healed only with great difficulty.

M. Curie has obtained a distinct reddening of the skin after an exposure to the rays of only eight minutes. This reddening appeared two months after the exposure, and did not produce any serious result. If the exposure is allowed to proceed for any considerable length of time, it leaves a permanent scar.

It seems probable that the use of radium may

supersede ultra-violet light, and the Rontgen rays, in the treatment of certain skin diseases. Cases have been reported where its action has resulted in the reduction of cancer growths. The author is not competent to judge how much confidence can be placed in these results; but the subject seems to be full of promise.

The rays seem also to have some effect in retarding the growth of bacteria in certain cases. They are able also to paralyse small animals, when the brain is exposed to their action. Death ensues soon after.

The leaves of plants are destroyed by the Becquerel rays. They turn yellow, and become friable. Lord Blythswood has remarked a similar effect on linen exposed to the rays. This also soon becomes quite brittle.

THE β-RAYS

We shall now describe the experiment which first gave a clue to the nature of the β-rays. This experiment shows that they are deflected by magnetic force. It was made at about the same time, though in somewhat different forms, by three independent sets of investigators—MM. Meyer and Sweidler, M. Geisel, and M. Becquerel.

There are many ways of making the magnetic deflection apparent. The simplest and crudest is to bring the radium salt near a photographic plate, wrapped in black paper. If no magnetic force is applied, the result will be a blurred patch, symmetrically disposed with regard to the position of the radium. If now a magnet is brought up so that one pole is on each side of the path of the rays, it will be found that the image obtained on development is no longer symmetrical, but is drawn out almost entirely on to one side. The direction of the deviation is at right

angles to the path of the rays, and to the line between the poles of the magnet. By turning the magnet over, so as to make its poles change places, the deflection takes place in the opposite direction to what it did before.

The same experiment can be made with a fluorescent screen instead of a photographic plate. If an electro-magnet is used, the luminosity is seen to be drawn out to one side when the current is sent one way, and to the opposite when it is reversed. The electrical method may also be used for detecting this deflection. M. Curie was the first to use it in this way. He placed the radium salt at the bottom of a narrow leaden vessel (fig. 12). This vessel was placed between the poles of an electro-magnet. When the magnet was not excited, the rays issuing from the mouth of the vessel fell on an electroscope, and this was accordingly discharged. But when the magnet was excited, the rays were curved and thrown against the side of the vessel, so that they could not get out, and their discharging effect was stopped. In this experiment it is necessary to have some inches' distance between the radio-active substance and the electroscope, so as to have a sufficient stratum of air to absorb the α-rays, and thus to experiment with the β-rays only.[1]

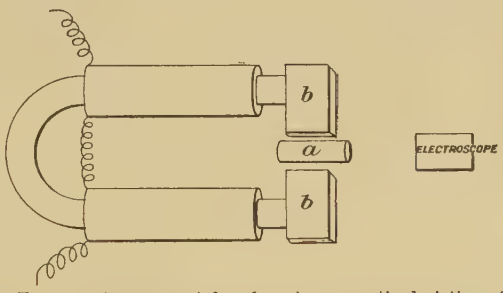


FIG. 12.—Arrangement for observing magnetic deviation of β-rays. A metal tube closed at one end contains the radium at the bottom. It is placed between the poles of an electro-magnet. When the magnet current is off, the rays can get out and fall on the electroscope, producing the usual discharging effect. When the magnet is on, they are thrown against the side of the tube, and cannot get out so as to affect the electroscope.

The magnetic deflection of the rays, as has been

[1] The γ-rays do not produce conspicuous effect in this experiment.

mentioned, was the first clue to their true nature. For it at once suggested that they were of the same nature of the cathode rays, and quite distinct from the Rontgen rays with which they were at first compared. The deflection of the β-rays is in the same direction as that of the cathode rays. We may here anticipate the experimental evidence, and state that there is overwhelming reason to conclude that the β-rays are indeed cathode rays; that they consist of negatively electrified projectiles fired out from the radio-active substance. It was a striking discovery that the phenomenon of the cathode rays, before only obtained by the use of complicated artificial appliances—batteries, induction coils, and mercurial air-pumps, was spontaneously shown by a chemical preparation, and even by a piece of stone (pitch-blende), just as it came from the earth. Scientific investigation often proceeds in the direction of complicating its appliances. But instances of the opposite tendency are not wanting.

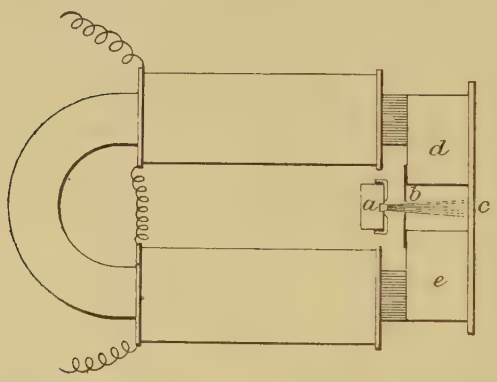


FIG. 13.—Another arrangement for observing the magnetic deviation of the β-rays. The radium is contained in a small capsule, *a*. Its rays pass through the small hole or slit, *b*, and fall on a photographic plate or fluorescent screen, *c*, after passing between the poles, *d*, *e*, of a magnet. When the current is on, the impression is displaced, and drawn out into an elongated form, in a direction perpendicular to the paper.

The methods of detecting the magneticdeflection which we have described, though sufficient for that purpose, are very crude; for they do not admit of more than qualitative observation. A more refined method is the following (fig. 13). The radio-active salt is placed in a very

narrow groove cut in a piece of metal. Over the groove, and parallel to it at a little distance, is placed a narrow slit, cut in a metal plate. The rays, issuing from the radio-active salt, pass through the slit, and are thereby confined to a narrow beam. This beam may be made to fall on a photographic plate, or on a fluorescent screen, perpendicular to it, and the impression will be a narrow line. If a magnetic force is applied across the path of the rays, and in the direction of the slit, the beam will be deflected. It is found, however, that the impression produced by the deflected rays is not a mere displacement of the impression produced by the original undeflected beam. It is many times broader.

We saw in the first chapter that the cathode rays, if produced by a steady and uniform discharge, were not at all spread out by magnetic deflection. They are all of the same velocity. With the cathode rays of radium it is otherwise. Their velocities vary over a wide range, some being much more deflected by magnetic force than others; this explains the broadening out of the impression formed by the rays.

If we consider the deflected rays which reach some given spot on the photographic plate, it is easy to measure the circle into which they are bent; for we know that their path must pass through three points —the narrow radio-active source, the slit, and the assigned spot on the plate (fig. 14). These three positions being known, it is easy to calculate the radius of the circle which passes through them. This is the desired result. It is found that the deflection of the β-rays is less than that of the cathode rays which can practically be produced by electric discharge, even in the best vacua in which the discharge can be got to pass at all. It is to be concluded that the rays emitted by radium move

more rapidly. We shall have more to say on the subject later on in this chapter.

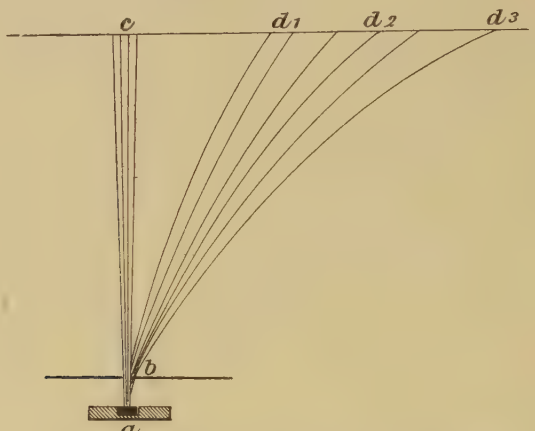


FIG. 14.—Magnetic spectrum of β-rays. Section of the path of the rays. At a the radium is placed in a narrow groove in a piece of metal. The rays pass through the slit, b, which confines them to a narrow beam. In the absence of magnetic force, they would fall on the plate at c, in a narrow band. When a magnetic force is applied perpendicular to the paper, the rays are bent to varying degrees, and reach the plate at various distances, d_1, d_2, d_3, from the undeflected position. Thus a broad band or spectrum is impressed on the plate.

Lenard found, as we have already seen, that the cathode rays produced a blue luminosity in the gas through which they pass. This luminosity is visible both inside the vacuum tube and outside it, though it is much more conspicuous inside in the neighbourhood of the cathode, especially where the pressure is not too low. This luminosity is called the negative glow, and possesses a spectrum characteristic of the gas in question.

Sir William and Lady Huggins have recently obtained evidence that the β-rays of radium also produce the same characteristic glow in gases. It was noticed in the early days of the discovery of radium that radium preparations were feebly self-luminous in the dark. It was generally thought that this was due to a slight fluorescence of the salt under the influence of its own rays—at least that was

the view which the author took of it, and probably others thought the same. Sir William and Lady Huggins, however, making use of their unrivalled experience in the photography of feeble spectra gained in working on the nebulæ, were able to photograph the spectrum of the radium glow, and they found it to give the characteristic bands of nitrogen. Thus it seems likely that the glow is due to the air, and is produced by the action of the β-rays upon it, just as the cathode rays produce luminosity in gases.

There is one outstanding difficulty about this explanation which ought to be noticed. The β-rays are most concentrated in the immediate neighbourhood of the radium, and no doubt it is to be expected that the glow should be strongest then. But it ought, one would think, to extend to some visible distance beyond the salt. This does not seem to be the case, for the glow appears to stop at the boundary of the solid. Professor Dewar has found that the nitrogen bands cannot be observed in the glow when the radium salt has been heated in a high vacuum so as to remove all nitrogen from its neighbourhood.[1]

The β-rays resemble the cathode rays in another way. They carry a negative electric charge with them. The radio-active substance loses this negative charge, and if it is insulated, it will become positively charged in consequence. On the other hand, anything which absorbs the rays necessarily receives the negative charge which they carry, and becomes negatively electrified. In short, a current

[1] Some very weak preparations of radium in the author's possession are quite as luminous, if not more so, than some pure radium bromide. This is difficult to understand. Moreover, a trace of moisture suffices to destroy the luminosity. Possibly a part of it really is in some cases due to fluorescence under the rays.

of negative electricity is constantly flowing spontaneously away from the radium.

It might seem to be the simplest matter possible to detect these effects. But such is not the case. The difficulties are two. In the first place, the current is exceedingly small, so that the amount of electricity hurled off by the radium in any moderate time is difficult to detect, unless we have a relatively considerable quantity of radium to work with. In the second place, it will be remembered that the rays are making the air all round them conduct electricity. The result is that the charge imparted by the rays to anything they fall upon is conducted away by the air as fast as it comes; and no charge can accumulate so as to be observed. M. and Mme. Curie were the first to succeed in detecting the charge. The plan used by them was very ingenious. They embedded the metal plate on which the rays were to play, in paraffin wax, which is an excellent insulator of electricity.[1]

This prevented the electricity from leaking away, although it allowed the β-rays to get through to a sufficient extent for the purpose (fig. 15). The result was that the plate became charged with negative electricity, and its charge could be made apparent by means of an electrometer. M. Curie also tried the

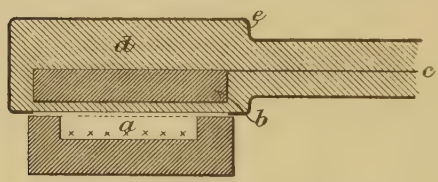


FIG. 15.—Section of Curie's apparatus for observing the charge conveyed by radium to surrounding conductors. *a* is the radium, contained in a cavity in a lead block. *b* is the block of lead which receives the rays, and becomes charged. It is entirely surrounded by paraffin wax, *d*. This prevents the charge acquired from leaking away. *b* is connected by the wire, *c*, to the electrometer, which indicates the charge acquired. The whole of the receiving arrangement is surrounded by a metal case, *e*, connected to earth, but this metal is very thin on the face where the rays enter.

[1] It is known that paraffin loses its insulation to some extent while under the influence of Becquerel rays; but apparently, to judge by the result, the failure of insulation is not serious enough to affect the use of paraffin in this experiment.

complementary experiment, to show that the negative electricity carried by the rays was lost by the radium. In this case it was necessary to surround the radium with a thin layer of paraffin. It then soon became charged with positive electricity, showing that negative electricity had been shot off from it.

A simple way of exhibiting this result was published a short time ago by the author. In this case, instead of using paraffin to prevent the escape of electrification, the alternative plan of removing the air is adopted. The radium is sealed up in a thin-walled glass tube, so that the rays can get out through the sides of the tube. The tube is coated with a conducting substance, and a pair of gold leaves, constituting an electroscope, are attached to it. The whole system is hung up in an exhausted vessel by an insulating support (fig. 16). The β-rays carry negative electricity away from the system. It becomes charged with positive electricity in consequence. The gold leaves begin to diverge,

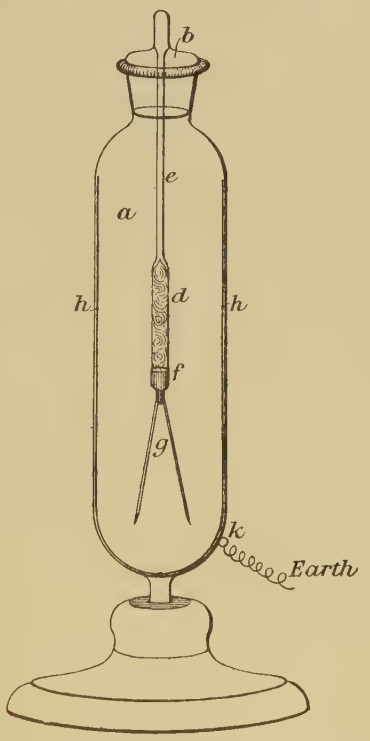


FIG. 16.—Arrangement for exhibiting the self-electrification of radium. A glass cylinder, *a*, is provided with a stopper, *b*. From this the thin glass tube, *d*, containing radium is hung by the glass rod, *e*, which serves as an insulating support. *d* is covered with a film of phosphoric acid, which makes it a conductor. At the other end is a brass cap, *f*, which carries the gold leaves, *g*. The whole is exhausted through *b*, which subsequently serves as a means of supporting it. *d* loses negative electricity, thus acquiring a positive charge, and the leaves, *g*, diverge. The divergence increases until the leaves touch the tinfoil strips, *h h*, which are connected to the earth through a wire, *k*, sealed into the glass. This touching discharges the leaves, but they begin to diverge again immediately, if the radium preparation is active. This oscillation of the leaves goes on indefinitely.

and the divergence steadily increases until they touch the walls of the containing vessel, and are discharged. Then they begin to charge up again, and so on indefinitely. The time that the leaves take to diverge and collapse again once depends, of course, on how much radium is used. But with several milligrammes of a pure radium salt, it is easy to make an apparatus which will go through its cycle in the course of a minute. This apparatus is probably the nearest approach to perpetual motion that has ever been attained. The divergence and collapse of the leaves is maintained without ceasing, and can only stop when the radium loses its activity. How long this may take, we do not very exactly know; but hundreds of years at least must elapse before the forces which cause the leaves to move have ceased to act.

Enough electricity has been accumulated by the self-electrification of radium, even to give an electric shock. It happened thus. Herr Dorn had sealed up some radium salt hermetically in a tube of glass which possessed good insulating power; the negative charge was shot out in the form of β-rays, while the positive charge remained in the tube, in which it was retained by the good insulation of the glass. This process went on for six months, after which time, the radium being wanted for some purpose, the tube was scratched with a file preparatory to breaking it. The scratched and weakened glass was no longer able to sustain the electric strain to which it was subjected, and it was perforated by an electric spark. At the same time a smart shock was felt, as the accumulated electric charge passed to earth through the experimenter's body. It may be asked, Is there any limit to the extent to which this self-charging of radium might proceed, if

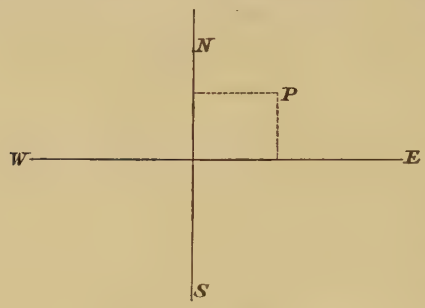
enough time were allowed? There is, of course, a practical limit in that the insulation with which the radium is surrounded would necessarily give way in time, and be ruptured by a spark, as in the case described. But there is another limit besides, even if that one could be removed, for the positive electricity left on the radium must hinder the escape of more negative electricity. It drags on the escaping negative particles; it attracts them back to the radium. The particles are shot out so fast that they can escape without being appreciably hindered by this in any practical case. But in the end, if enough positive electricity had accumulated, it could not fail to hold the negative particles back, and altogether prevent their escape.

The β-rays, like the cathode rays, are deflected when an electric force acts at right angles to their path. This was first proved by M. Becquerel, but, instead of describing his original experiments, we shall speak of some later ones made by Professor Kauffmann, which show it more clearly, and enable the electrostatic deflection to be compared with the magnetic.

The principle of these experiments is very ingenious. It is briefly this. A narrow and sharply defined beam of rays from radium falls perpendicularly on a photographic plate. A magnetic force is applied at right angles to the direction of the rays, and sorts them out according to their velocities; the fastest particles are deflected from their path the least, the slowest particles are deflected the most. Before the magnetic force was applied, the rays all fell on one spot in the centre of the plate. Now that the magnetic force acts, they are spread out so as to fall on a straight line.

Now we apply in addition an electric force, so as

to deflect the rays, just as the magnetic did, but in the perpendicular direction. This too, by itself, would spread out the rays and cause them to intersect the plate along a straight line at right angles to the former one. But we must remember that the magnetic force is acting simultaneously, though independently. What will happen? Every particle which we might think of as moving vertically will be deflected to a certain extent, say northwards, by the magnetic force; to a certain extent in the perpendicular direction eastwards, by the electrostatic force. The result must be that it strikes the plate somewhere in the region between the north and east lines—somewhere in the right-hand top region of this diagram, say at the point P.



Since particles are present which have continuously varying velocity, the impression on the plate will be a curve. Each point on this curve will correspond to some particular velocity. The perpendicular distance of the point from the NS line, the distance eastwards, that is, measures the electrostatic deflection. The perpendicular distance from the EW line measures the magnetic deflection in the same way.

This is the principle of the experiment. It is now time to say something of the practical details. The source of the rays was a small speck of radium bromide, and the rays were confined into a definite beam by passing through a round hole in a metal plate. The rays, in passing from the radium to the hole, had to pass between two parallel metal plates,

which were kept at a great potential difference, by means of a special arrangement, into the details of which we need not enter. After passing through the hole, the rays had to traverse a further interval, and then fell on the photographic plate. The whole arrangement was enclosed in glass, and the air completely pumped out. This was necessary, partly to avoid the diffusion and absorption of the rays by air, partly to prevent an electric discharge between the plates used to produce electrostatic deflection. The whole arrangement was placed between the poles of a large magnet, so as to subject the rays to a uniform magnetic force along their whole length.

The exposure of the plates had to last many hours in order to get a visible impression.

It was possible, by measuring the position of various points on the photographic curve, to find the magnetic and electrostatic deflection corresponding to each point. Each point represents the impact of particles of some particular velocity, so that a series of values was obtained for particles of various velocities. We saw, in the first chapter, how a knowledge of the magnetic and electrostatic deflection of the cathode rays could be used to calculate the speed and electro-chemical equivalent of the particles. Professor Kauffmann used his measurements to obtain this information. The results are very interesting and important. They are as follows :—

Velocity, centimetres per second.	Ratio of charge to mass.
2·83	$\cdot 63 \times 10^7$
2·72	$\cdot 77 \times 10^7$
2·59	$\cdot 97 \times 10^7$
2·48	$1 \cdot 17 \times 10^7$
2·36	$1 \cdot 31 \times 10^7$

The velocity of light is 3×10^{10} centimetres per second, so that the β-particles are projected with a speed nearly equal to this.

It is difficult fully to grasp the significance of this amazing result. The apparently quiescent little speck of white salt is hurling off projectiles with a speed something like half a million times the speed of a cannon-ball.

We see that the β-particles of radium are some ten times more rapid than the cathode rays. They move much faster than any other natural body that is known in the universe.

It will be noticed that the mass of the β-particles does not seem to remain constant when compared to the charge, for the ratio between them varies in Professor Kauffmann's experiments over a twofold range.

This is at first sight difficult to understand; for we have seen that the charge of electricity carried by the particles of the cathode rays is in all probability the same as the charge of a hydrogen atom; and this charge is believed to be fixed and indivisible. We might have a charged particle carrying exactly twice as much electricity as the hydrogen atom, or exactly three times as much. But, unless the clearest proof compels it, the existence of intermediate charges cannot be admitted. There is an alternative possibility, and that is that the particles have not all the same mass—that some have more inertia than others. If this could be admitted, it would explain why the ratio of charge to mass should alter. The particles with the highest speed are those which (if the charge is always the same) have also the largest mass. If some of the particles are more massive than others, it is not apparent, at first sight, why those shot out the fastest should be the most massive. Exactly the contrary might perhaps be expected.

Electro-magnetic theory beautifully accounts for this. Some attempt must be made to follow the explanation, though in truth the subject is not well suited to an elementary book. The explanation will probably only be intelligible to those who have some idea of the phenomena of electro-magnetic induction.

Consider the motion of a charged particle. This constitutes an electric current, and sets up a magnetic force in the surrounding space. Now to set up a magnetic force requires the expenditure of energy. Where did this energy come from? Evidently from the source which set the particle in motion. So it is more difficult to set a particle in motion, if the particle is electrified, than if it is not. In other words, an electrified particle behaves as if it had a greater mass than one which is not electrified.

Now the ordinary mechanical mass of the particle does not depend at all on whether it is moving or not, or on whether the motion is fast or slow. The mass of a 10 lb. cannon-ball remains 10 lbs., whether the ball is in the magazine, or whether it is flying from the mouth of a gun. We must inquire closely whether the same is true of the spurious mass which a particle gets when it is electrified.

The magnetic force produced by the motion is proportional to the speed. The energy which it takes to produce the magnetic force is proportional to the square of the magnetic force, and consequently to the square of the speed. But the energy of a simple, constant mass is also proportional to the square of the speed. In other words, the electrical mass behaves just like the ordinary mechanical one, and does not depend on the speed at all.

All this is on the assumption that there is nothing to take into account except the magnetic force produced by the motion of the charged particle.

But there *is* something else which must be taken into account. There is an electric force induced by the motion of the lines of magnetic force which have been called into being by the motion of the charge.

Now the establishment of this electric force requires energy too, just as the original magnetic force does. This electric force depends on the strength of the magnetic force, and on the rate of motion. But the magnetic force itself depends on the rate of motion; so that the strength of the electric force depends on the rate of motion twice over, or, in other words, on the square of the speed of the particle.

Now the production of this electric field adds to the apparent mass of the particle just as the production of the magnetic field did. But there is this important distinction. The added energy of motion, which is proportional to the square of the electric force, must be proportional to the fourth power of the speed, instead of being proportional to the square of it; so that the addition of mass due to the induced electric force depends on the speed, and becomes greater the greater the speed is.

To calculate exactly the mass at any given speed is a difficult problem, and there is a want of unanimity among the highest authorities on the subject. But all are agreed that the increase of mass is unimportant until the speed of light is approached, but that the apparent mass then rapidly increases. It is believed that when the speed of light is reached the mass becomes infinite—in fact, that unlimited energy would be required to make an electric charge move so fast as that, and that consequently it never *could* move so fast.

The particles of the cathode stream produced by electric discharge do not move more than one-third of the velocity of light, even when the conditions are

as favourable to the attainment of a high speed as it is possible in practice to make them. More ordinarily their velocity does not much exceed one-tenth of the velocity of light. But even if one-third of the velocity of light is attained, the increased inertia would scarcely be sufficient to be of practical importance.

It is otherwise with the cathode rays of high velocity produced by radium, for the velocity of light is nearly approached by them.

The trend of what has been said will now be apparent. It is reasonable to assume that the apparently increased mass of the faster moving particles is due to their electrical inertia, which might be expected to increase in quite a similar way.

It is very important to know whether the whole mass of the particles is electrical, or whether part of it is mechanical and independent of speed. Kauffmann's experiments give the means of testing this to a certain extent, for we can compare the masses at different speeds, and see whether the increase of mass with increasing speed is as fast as it ought to be if the mass was wholly electrical. Professor Kauffmann is of opinion that his experiments are most consistent with the view that the mass is altogether of electrical origin—that the β-particles are, in fact, disembodied charges of negative electricity, without any material substratum. It is too soon to accept this conclusion without reserve, for the assumptions involved in the calculations are dubious, and the accuracy attainable in the experiments is not sufficient to put the theory to a very severe test.

But, when all this has been admitted, the simplicity of the conclusion is very attractive, and it has gained a great deal of support during the last two years from current scientific opinion.

There is one misconception which must be carefully

guarded against. In speaking of the mass of a charged particle, the effects of inertia have alone been referred to. It is an undeniable inference from known facts that the inertia of a body must be greater when it is electrified. It necessarily becomes more difficult to set in motion than before, though, in any case within ordinary experience, their increase would be too small to detect. We could not, for instance, give any electric charge to a rifle bullet which would make its inertia measurably greater. But, in the light of electrical theory, there is no doubt at all that the inertia has really been increased.

When we come to consider the *weight* of the body, the force, that is, with which the earth attracts it, we have no means of judging whether or not the electrification produces any effect.[1] In all ordinary cases inertia and weight are inseparably associated. But whether the inertia of electrical origin is accompanied by corresponding weight, we do not know at all. No experiment has been devised by which the question can be tested. Indeed, as we do not know why gravitation accompanies ordinary inertia, it is not surprising that we are unable to decide theoretically whether it should accompany electrical inertia or not.

THE α-RAYS

We have seen that the β-rays are in all respects similar to the cathode rays set in motion by an electric discharge in a vacuum tube. The β-rays, however, though in some respects the most conspicuous, are by no means the most important feature of radio-activity. By far the greatest part of the discharging power is due to the α-rays, and it is now time to consider these.

[1] The electrical attraction on surrounding conductors has, of course, nothing to do with this.

The β-rays were easily shown to be deflected by a magnetic force. For a long time it was thought that the α-rays were not at all affected by magnetic force. We now know that they too are bent, but to a much less extent, and in the opposite direction to the β-rays.

This result is due to the skill and perseverance of Professor Rutherford, and it is of far-reaching importance. We shall now describe the method used by him for detecting the deflection. The observation is difficult because of the extreme smallness of the curvature which can be produced even by a very strong magnetic force.

The experiment is in principle exactly the same as M. Curie's experiment to show the deflection of the β-rays (fig. 12). But refinements are necessary in this case which were not called for in that.

The method, it will be remembered, is to place the radium at the bottom of a narrow vessel, and to place the vessel between the poles of an electro-magnet. When the magnet is not excited, the rays follow a straight course, and are able to issue from the mouth of the vessel, whence they penetrate into an electroscope, and cause the gold leaf to collapse. But when the magnet is in action, the rays are bent into a curve, and fall on the sides of the vessel, which stop them. Thus they cannot get out of the vessel, and the electroscope is not discharged.

In the case of the α-rays, it is only possible to produce a very slight curvature of the rays. Thus the vessel at the bottom of which the radium is placed must be made very narrow. It must consist of a mere slit between two parallel metal plates; for if the plates were not very close, the rays could get out in spite of their slight curvature.

It is evident that one such slit cannot give out very much radiation, on account of its narrowness. To get enough rays to work with conveniently, it is necessary to have a number of parallel slits, so that the radium is placed in a layer at the bottom of a box containing a number of parallel plates, with narrow spaces between. The rays come through these narrow interspaces and enter the electroscope (fig. 17).

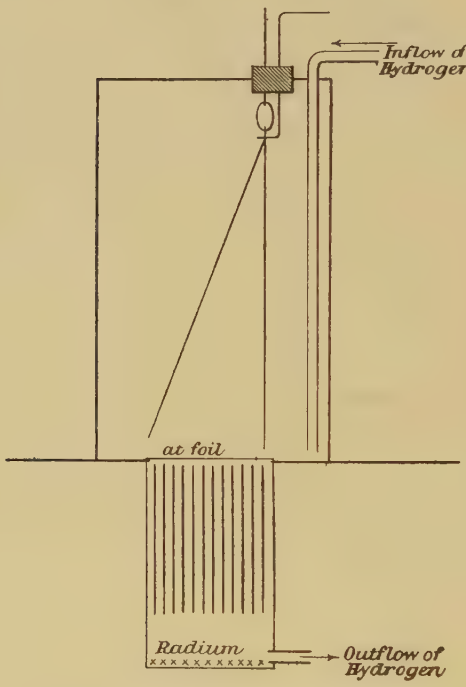


FIG. 17.—Rutherford's arrangement for observing magnetic deviation of α-rays. The rays pass up between the metal slits, and enter the electroscope, causing discharge. When a magnetic field is applied perpendicular to the paper, the rays are curved, and can no longer get through the slits. Thus discharge is stopped.

It is necessary that the narrow slits should be reasonably long in order that the magnetic force may act on the rays along a considerable length. Air, however, absorbs the α-rays very freely, and if air filled the spaces, practically no rays would get through. We cannot exhaust the entire apparatus, for the presence of some gas in the electroscope is necessary to enable the rays to discharge; and we cannot exhaust the slits without exhausting the electroscope, for it would be impracticable to make an air-tight partition thin enough to let the α-rays get through. The difficulty was got over by

filling the apparatus with hydrogen, which is much less opaque to the rays than air.

The vessel with the series of slits was placed between the poles of a large and powerful electromagnet, so that the lines of magnetic force lay in the same direction as the series of parallel plates, but crossed the path of the rays at right angles. Under these circumstances it was found that the discharge of the electroscope was almost stopped when the magnet was strongly excited. The α-rays had been deflected.

The experiment in this form does not show in which direction the deflection takes place—whether it is in the same direction as for the β-rays, or in the opposite. It was necessary to modify it in order to test this important point. For this purpose a little ledge was made to project over one side of each plate (fig. 18). It will readily be understood that with such a ledge the rays could get out more when they were deflected to the side away from the ledge than when they were bent so as to be intercepted by it. The rate of leak was accordingly greater with magnetic force one way than when it was reversed. By this means the direction of deflection could be inferred, and it was found to be opposite to that of the cathode rays.

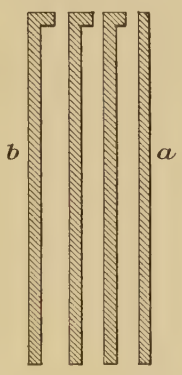


FIG. 18. — Arrangement of ledges for determining direction in which the rays are bent. The rays can get through when bent so as to be concave to a. When bent so as to be concave to b they are stopped by the ledges.

The argument which showed that the β-rays were negatively charged particles is equally applicable to prove that the α-rays are positively charged ones.

It is found that the α-rays are deflected by an electrostatic force, just as the β-rays are. This experiment is even more difficult than the corre-

sponding magnetic one which we have just described. It was carried out by Professor Rutherford in quite a similar way. A series of parallel brass plates were used, but in this case it was necessary to insulate them from one another by holding them at the sides with ebonite. The alternate plates were connected together, just like the plates of a storage cell, and an electric force was made to act between each plate and its neighbour by connecting the two sets of plates to the poles of a battery consisting of many cells.

It was a great difficulty in the experiment that only a moderate electric force could be applied between the plates; for if more was attempted, a luminous electric discharge was produced between the plates. This limitation made it very difficult to deflect the rays completely, but still unmistakable evidence of the deflection was obtained.

No one has yet succeeded in demonstrating directly that the α-rays carry a positive charge, though there can be no reasonable doubt of the fact that they do so. The difficulty is the same as that which was overcome in the case of the β-rays by exhausting the vessel or by the use of a solid insulator. With the α-rays we cannot use a solid insulator, for they are scarcely able to penetrate it. And all attempts to use the method of exhaustion have failed. The reason is that the conduction produced by the α-rays is very large, and even at the best vacua there is still enough conduction to enable the charge to leak away faster than it can accumulate.[1] Another point which must not be overlooked is that in the case of radium the negative charge carried with the β-rays will partially or

[1] The author has recently satisfied himself that a charged polonium rod loses its charge even in complete absence of air. This seems to indicate that ions are torn off from the solid by the issuing α-particle, and carry the current. There seems, therefore, to be no chance of detecting the charge of the α-rays.

perhaps wholly neutralise the positive one due to the α-rays. Radio-active substances exist which only give out α-rays. Polonium is one of these, and it will no doubt be best to employ it in future attempts to detect the charge carried by these rays.

By measuring the magnetic and electrostatic forces necessary to completely deviate the rays, Professor Rutherford was able to estimate the curvature of the rays produced by a given electric or magnetic force, though it is not to be expected that a measurement of this kind should give results of great precision. From these data we can reason exactly as for the cathode rays; and the result is to show that, for the α-rays, the ratio of charge to mass, or electro-chemical equivalent, is about the same as for an atom of hydrogen. The velocity comes out about $\frac{1}{10}$ of the velocity of light.

Thus the α-rays are very similar to the canal rays of a vacuum discharge (see chap. i. p. 23).

M. Becquerel has been able to confirm Professor Rutherford's observations on the magnetic deviations of the α-rays. He used the photographic method. The radio-active substance was placed in a narrow groove in a piece of lead. A little distance above it was a slit parallel to the groove. The rays were confined by this means to a flat, narrow beam, like the blade of a chisel. A photographic plate was placed in a slanting position so that the beam grazed along its surface. The image on the plate, after development, gave a picture of the path which the rays had pursued. The whole arrangement was placed between the poles of a powerful electro-magnet. It was necessary to give a long exposure. After a sufficient exposure, the current was sent the opposite way through the magnet and another equal exposure given. On developing the plate it was found that the

rays had been bent by the magnetic force to a curved path. The two trajectories of the rays curved away in opposite directions from the central line (fig. 19); each corresponded to a different direction of the magnetic force. By measuring the distance apart of the two trajectories, the deflection of the rays could be quantitatively estimated. The result was in good agreement with Professor Rutherford's estimate.

Fig. 19.—Figure representing Becquerel's photographs of the path of the α-rays under a magnetic force. The rays are confined into a narrow beam, and graze the plate. They are curved by the magnetic force, which is supposed to work at right angles to the plane of the paper. One branch gives the path of the rays when the magnetic force acts downwards, the other when it acts upwards.

The result to which we have alluded, that the electrochemical equivalent of the α-particles is nearly the same as for a hydrogen atom, is of very great importance. The electrochemical equivalent is, as we have seen, the quantity of electricity transported by unit mass of the substance, or, what amounts to the same thing, the ratio of the electric charge of each particle to its mass. We cannot assume that the masses of the α-particles are the same as the masses of the hydrogen atoms until we know that the charge of electricity carried is the same.

It cannot be said that we do know this with any certainty. But it will appear in the sequel that there are strong reasons for suspecting it. If we assume it to be true, it would follow that the mass of the

particle is (nearly at all events) the same as the mass of an atom of hydrogen, and if that is so, the inference is almost irresistible that the two are identical.

Hydrogen has the lowest atomic weight of all the elements—its atom is the lightest. The next is helium, with an atom four times as heavy. The helium atom may be supposed to be capable of carrying the same charge of electricity as the hydrogen atom, though this again is a matter of which we have no direct knowledge. In that case, its electrochemical equivalent would be four times greater. The actual measurements on the α-rays point to a number about half as large again as for hydrogen, but they are scarcely sufficiently precise to distinguish between a hydrogen atom and an atom of helium.

It will be remembered that the β-particles, or corpuscles, of radium were not all ejected with equal velocity. Some of them moved much more rapidly than others, and the result was that a pencil of the rays was splayed out into a fan-shape by magnetic force. This is not found to be the case with the α-rays; M. Becquerel's photographs show that the α-rays are not dispersed by magnetic deflection, or, at all events, very little. It is to be concluded that (with a given radio-active substance) they are all shot out at about the same speed.

Sir William Crookes has made a very interesting observation on the phosphorescence produced by the α-rays. He brought a tiny speck of radium a short distance off a zinc sulphide screen, and examined the resulting fluorescent light with a magnifying lens. He found that the fluorescence did not proceed uniformly from all parts of the screen, but that it came from isolated points dotted about on the surface. These points are constantly shifting about, and their

appearance is very suggestive of the splashing of raindrops on a pond. This appearance is only produced by the α-rays. The more penetrating kinds of rays produce a uniform fluorescence, without scintillations, and so do the Rontgen rays from an exhausted tube.

Sir William Crookes's experiment is easily repeated. A zinc sulphide screen is much better for the purpose than a platino-cyanide one. A small piece of apparatus, consisting of a zinc sulphide screen, a small speck of radium in front of it, and a suitable magnifying lens, all mounted in a brass tube, has been designed by him for showing the effect, and named a spinthariscope. The simple and direct interpretation of the luminous specks is that each speck corresponds to the impact of an α-particle on the phosphorescent screen. This was the view adopted by Sir William Crookes, and generally accepted. Though the explanation seems at first sight simple and satisfactory, M. Becquerel has urged strong arguments in favour of an alternative theory.

He is of opinion that, though the phenomena are no doubt due to the impact of the α-particles, each flash corresponds not to the impact of one particle, but to the fracture of a crystal of the phosphorescent substance by the battering which it gets from the α-particles. Such a fracture will probably not occur every time a particle strikes, but rather when a number of particles happen to assault a weak spot on the crystal simultaneously. The emission of light by crystals in breaking is quite a familiar fact. Any one can observe it for himself by grinding two lumps of sugar together in the dark. M. Becquerel has been able to imitate the spinthariscope by the crushing of a crystal of zinc sulphide mechanically. When the light emitted was examined by a lens, the characteristic scintillating spots were observed. He has

found, moreover, that the scintillations produced by radium are more numerous when the zinc sulphide screen consists of small crystals than when it consists of large ones. This proves conclusively that the impact of an α-particle does not necessarily produce a scintillation; and it is favourable to the fracture theory, for naturally small crystals would be more easily broken by impact than large ones. Although this theory is less attractive than the original one, the balance of evidence seems to be in its favour. Whichever be adopted, the spinthariscope affords an interesting illustration of the mechanical nature of the α-radiation.

THE γ-RAYS OF RADIUM

It remains to deal with the most penetrating kind of rays—those known as the γ-rays. Their most striking characteristic is the great penetrating power, for they are able to make their way through massive blocks of iron or lead. I have succeeded in observing the γ-radiation from 10 milligrammes of radium bromide, even through a thickness of 8 cm. (nearly three inches) of solid lead, and there would be no difficulty in observing their effect through 6 inches of iron. In such observations the electrical method is of course used, for it is much the most sensitive.

We have less information about the γ-rays of radium than about either of the other three varieties. The feature which distinguishes them from the more penetrating kind of β-rays is the absence of the characteristic magnetic deflection. No experiment has yet succeeded in deflecting them by magnetic force. Some observations have been made which seem at first sight to suggest that they carry an electric charge. But there is reason to doubt whether they are conclusive.

Uranium and thorium as well as radium emit γ-rays. Polonium, however, does not do so. In fact, the substances which emit β-rays all emit γ-rays; and γ-rays are never, so far as we know, unaccompanied by β-rays. We shall see in a later chapter that radio-active products have been obtained from thorium, radium, and uranium, whose activity diminishes with time. In such cases the γ-radiation only appears in conjunction with the β-radiation, and always bears a fixed proportion to it. The nature of the γ-rays is one of the most obscure questions in connection with radio-activity. It will be interesting to consider the merits of two alternative theories. The view which is most popular is that which considers the γ-rays to be Rontgen rays, generated by the β-rays in striking the radium itself, or the absorbent screen, if such be used. There is much to recommend such a view. For we have seen that the β-rays are identical with cathode rays, and cathode rays, when they strike a solid obstacle, generate Rontgen rays, which are far more able to penetrate matter than the cathode rays themselves. Thus the relation between the β-rays and γ-rays seems to be closely analogous to the relation between the cathode rays in a vacuum tube, and the Rontgen rays which they produce, when they strike a solid obstacle. The invariable appearance of the two kinds of rays in company is very well accounted for by this theory. Moreover, the γ-rays resemble Rontgen rays in their complete indifference to magnetic force.

Simple and satisfactory as this view of the γ-rays now appears, there have been formidable objections to it. We shall be in a position to understand these when the absorption of the rays by solids and the ionisation which they produce in gases comes to be discussed.

The other alternative is to consider that the γ-rays are corpuscular, like the β-rays. This is easy to reconcile with most of the facts. The mutual companionship of the β- and γ-rays is thus intelligible, and the phenomena of absorption and ionisation, to which we have just alluded, are fully in accordance with it. The great objection is the absence of magnetic deflection. It must, indeed, be remembered that the amount of magnetic deflection depends on the velocity of the particles, and that if this velocity were sufficiently high, the magnetic effect might be too small for experimental detection. It would be very important to know more definitely whether or not there is a continuous transition between the β- and γ-rays—whether β-rays exist which just, but only just, show visible deflection in a strong magnetic field. If this were found to be the case, it would be in favour of the theory that the γ-rays were only an extreme variety of the β-rays. In any case it would seem that there must be Rontgen rays, produced by the cathodic β-rays. But these might not be sufficiently conspicuous to produce visible effects.

Professor Paschen has found that radium encased in thick lead, so as to let out only the γ-rays, still gained a positive charge when insulated. This experiment was made by means of an electroscope apparatus similar to that described above (p. 34). He regards this as proving that these rays carry a negative charge. It must be remembered, however, that when the Rontgen rays fall on a metal surface, they set up secondary rays, which carry a negative electric charge—which are, in fact, cathode rays. Paschen's experiment is open to the objection that the charge observed by him may be due to such rays set up at the surface of the lead by the γ-rays, and

is not necessarily a proof that the γ-rays themselves are of a corpuscular nature. It is not inconsistent with the alternative view that they are Rontgen rays.

Let us now sum up our conclusions with regard to the three kinds of rays emitted by radium. Fig. 20, due to Mme. Curie, exhibits diagrammatically the behaviour of the three kinds of rays in a magnetic field. The α-rays, giving rise to by far the greater part of the electrical effect, are slightly deflected by a transverse magnetic force, in that direction which corresponds to an emission of positively charged masses. Measurements of the ratio of charge to mass suggest that they are comparable in mass to hydrogen or helium atoms.

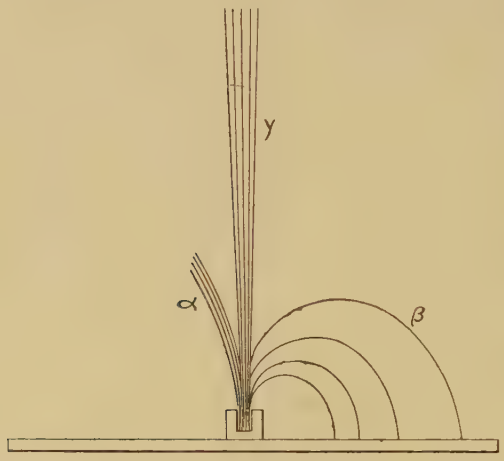


FIG. 20.—Diagram illustrative of the behaviour of the three varieties of Becquerel rays in a field of magnetic force. The α-rays are bent very slightly in one direction. The β-rays are bent very much in the opposite direction; while the γ-rays are not bent at all.

The β-rays, which are principally instrumental in producing the photographic effect, are deflected in the opposite direction to the α-rays, and consist of negatively charged corpuscles of much less than atomic dimensions.

The γ-rays, not deflected at all by magnetic force, are probably Rontgen rays, produced by the cathodic β-rays.

CHAPTER IV

ABSORPTION AND IONISATION

We have already seen that the three varieties of rays emitted by radium can be separated by means of solid screens. Very thin screens allow all three kinds of rays to pass. Screens of moderate thickness suppress the α-rays, leaving the β- and γ-rays. Very thick screens allow the γ-rays only to pass. It is now time to consider the absorption of the rays by solids somewhat more in detail.

For studying the α-rays, it is convenient to make use of polonium. For polonium emits these rays only, and the effects are not complicated by the presence of the other kinds.

In the first place, the α-rays are absorbed with extraordinary facility by the air. For they can only penetrate for a very small distance in the air—not more than two inches, if so much.

It was found by Mme. Curie that the percentage of the polonium rays, transmitted through a leaf of aluminium $\frac{1}{100}$ millimetre thick, was greater when the rays had to traverse a considerable thickness of air than when they had only a short distance to traverse. For instance, it was found that when the rays had to traverse 1·9 cm. of air, 5 per cent. only survived passage through an aluminium leaf. But when only ·5 cm. of air lay between the polonium and the apparatus for measuring the electrical effect, then 25 per cent. of the radiation was able to pass

the leaf. It would appear, therefore, that the penetrating power of the rays is diminished by passing through the air.

It seems that the most probable explanation is as follows :—

We know that the rays consist of particles comparable in mass with the atoms of hydrogen. In passing through the air, these must make many collisions with the molecules of the latter. Now, we have reason to think that the α-particles are all shot out with about the same velocity : for, as we have seen, they are all deflected to something like the same extent by magnetic force. Thus, every particle has, in the first instance, the same chance of penetrating the absorbent screen. Now some particles will be stopped altogether by the air. Others will be partially hindered and their speed reduced by grazing collisions with the air molecules. The further the particles have to go through the air, the larger will be the proportion of the survivors which have undergone such hindrance ; so that the average velocity will be smaller the further the particles have gone ; and their power of penetrating the aluminium leaf will be proportionately reduced.

This seems a plausible interpretation of the observed facts. But, in the present state of our knowledge, it must be admitted to be speculative, and must be received with due caution.

Experiments made by Professor Rutherford and Miss Brooks have shown that the absorption of the α-rays by different substances is nearly proportional to the densities of those substances. For instance, aluminium is some two thousand times heavier than air, and it is found that a layer of aluminium will reduce the rays to about the same extent as a layer of air two thousand times thicker. The *weight* of

the air interposed is the same as the *weight* of the aluminium leaf, provided, of course, that we take a stratum of the same cross-section in each case. The law applies to most substances which have as yet been tried. It is not accurate in every case. Tin, for instance, is considerably less absorbent than the law would require.

It has been found that the α-rays from various radio-active bodies differ somewhat in penetrating power. These differences are not, however, very great. They are probably due to a different velocity of the particles, though it cannot yet be considered quite certain that the α-particles are the same in every case—that uranium, for instance, emits exactly the same kind of α-particles as radium.

The absorption of the β-rays may next be considered.

We have already seen that a pencil of the β-rays of radium is spread out into a variety of different kinds of magnetic force, and that these varieties correspond to different velocities of the corpuscles. The rays least bent by the magnet are constituted by the faster moving corpuscles; the more deviable rays by the slower ones. Since the β-rays of radium are so complex, we cannot expect that the absorption phenomena will be simple. And experiment certainly shows that they are not; for it is found that after each successive absorption the rays which are left are more penetrating (on the whole) than before.

For instance, in an experiment of Mme. Curie, the β-rays were absorbed by successive thicknesses of lead, each equal to ·155 mm. It was found that the first sheet suppressed 60 per cent. of the radiation falling on it. The succeeding ones each suppressed a smaller percentage of what remained, until the

ninth sheet suppressed only 3 per cent. of the radiation which had penetrated the first eight.

A probable explanation seems to be this :—

The β-rays are of various velocities. The fast-moving corpuscles are able to penetrate further through matter than the others before they are stopped. Thus, after penetrating a sheet of metal, the percentage of fast-moving corpuscles is increased, and the power of penetrating a new sheet of metal is greater than at first.

An experiment by M. Becquerel shows in a very direct and satisfactory manner that the faster-moving corpuscles are indeed those which have the greatest penetrating power. It was explained in a former chapter how the rays could be sorted out into a spectrum by magnetic deflection, the fastest-moving corpuscles being the least deflected. M. Becquerel received the magnetic spectrum on a photographic plate, arranging strips of various absorbent material on the plate, so that the spectrum fell perpendicularly upon them. On development, it was found that the intensity of the spectrum was always more diminished by absorption at that end which corresponded to large deflection, or small corpuscular velocity. Practically, it was found that rays of less than a certain critical velocity were almost completely absorbed by each screen. The limiting velocity in question was of course lower for thin screens than for thick ones, and also lower for screens of dense material than for screens of light material.

Since there is a fairly well-defined minimum velocity for penetration of a screen, the penetrating power of a corpuscle must increase very rapidly with increasing velocity. Exact measurements of penetrating power in different regions of the magnetic spectrum would be of great value.

By covering the radium salt with a sufficient thickness of metal, we can suppress the β-rays altogether. The γ-rays then alone remain; but it is found that a very considerable thickness of lead is required to effect this. Some of the β-corpuscles are able to penetrate a sheet of lead one-tenth inch thick.

This fact is not a little remarkable. We saw that the cathode rays were able to penetrate very thin metal foil. The fact that they could do so was at one time regarded as a fatal objection to the view that they were of a corpuscular nature. But conclusive proof has since been forthcoming to show that they are so, and the same applies to the β-rays of radium. There are considerations which may help to explain the difficulty.

We must remember that Kauffmann's experiments showed that some of the β-particles are moving with a velocity very little inferior to that of light. Now as we have seen, a charged corpuscle moving with such a speed will have a momentum out of all proportion to what it would have according to the laws of ordinary mechanics, if the same laws held good for speeds like this that hold good for any speed of which we have experience in an ordinary way. The additional inertia, there is reason to believe, would become infinite if the speed of light was actually attained. Nothing could stop the corpuscle under such conditions. It will be understood, therefore, that great penetrating power is quite consistent with the known speed of the corpuscles, slightly inferior to that of light.

Further consideration of how to explain the penetration of solids by the rays must be deferred to the last chapter.

Since the β-rays of radium are so varied in their penetrating power, it is difficult to compare their

absorption by various substances. The β-rays of uranium have been found to be very much more homogeneous, and thus it is easier to obtain definite results with them. It has been found that as in the case of α-rays, the law of density is an approximation to the truth. The absorption is nearly in proportion to the density of the absorbing material (Plate III.). There are exceptions to the law. For instance, the metals tin and lead give excessive absorptions when compared with most other substances. They are even more absorbent than their high density would require. It is noteworthy that tin departs from the law of density in exactly the opposite direction when the absorption of the α-rays is in question.

With regard to the γ-rays, the available data are not very extensive. Professor Rutherford has, however, examined the comparative absorption of these rays by various substances. He found that in their case too the law of density was approximately obeyed.

The exceptions are not always the same as those for the β-rays. Thus, for instance, tin, which is very anomalous for the β-rays, is not much so for the γ-rays. Lead, on the other hand, is anomalous for the γ-rays, and for the β-rays also.

Some experiments by the author seem to make it probable that the excessive absorption of the γ-rays by certain metals is connected with the emission of secondary rays by those metals. If this view is correct, it must be assumed that two distinct causes are at work in producing absorption. One of these kinds of absorption which is ordinarily much the more important, depends only on the density of the substance. The other kind, which is only important in certain substances, depends on the power which these substances possess of transforming the γ-rays which fall upon them into a variety of rays

which have much less penetrating power. This action is analogous to fluorescence in optics—the property which some substances, such as acidulated quinine, possess of sending out light waves longer than those which fall upon them. The process involves absorption of the incident waves. The absorption which accompanies fluorescence too is of an exceptional nature; for ordinary absorption is not accompanied by fluorescence.

In what has been said of the absorption of γ-rays it has been tacitly assumed that they are all of one uniform kind. This is approximately true; it is found, however, that the rays which have passed through great thicknesses of lead—several centimetres—are somewhat more penetrating than those which have only traversed one centimetre.[1]

We have often alluded to the property which the Becquerel rays possess of causing the discharge of electrified bodies. This property was one of the first to be discovered, and it gives us the most generally useful method of detecting the presence of the rays, and measuring their comparative strength. It is now time to consider this important subject in detail.

In experiments on the electrical conduction under various conditions, the simple gold-leaf electroscope which we have hitherto supposed to be used, is scarcely available, and it is necessary to make use of a quadrant electrometer. It is desirable that the reader should make himself acquainted with the principle of that instrument, for the greater part of the experiments on radio-activity have involved its use. A description of it will be found in elementary works on electricity. It must suffice here to state that it enables us to measure small quantities of

[1] Professor M'Clelland has recently found that these most penetrating rays of all obey the law of density very closely.

electricity. When the instrument is set up in working order, and a charge of electricity imparted to it, the needle is deflected, to an extent proportional to the potential or electric pressure which results. A potential of one volt, which is about what can be got from some forms of battery cell, will often suffice to give a deflection of one hundred scale divisions on the electrometer, though improved electrometers have recently been devised which will give much more. The quantity of electricity which is required to charge the needle to one volt is very small. Accordingly a very small current of electricity flowing to the electrometer will cause its deflection to increase; the rate at which the electrometer needle is moving serves to measure the current which is flowing to it. It is found in practice that very much smaller currents can be detected and measured in this way than by the galvanometer; though, when the current is large enough, the latter instrument is more convenient.

A convenient piece of apparatus for experimenting on the electrical effect is illustrated in the figure (fig. 21). Two parallel metal plates are used. The radio-active substance is placed on the bottom plate, spread into a uniform layer. This bottom plate can be charged to any desired potential or electric pressure by means of a battery. The plate above is connected to the electrometer, and is initially uncharged. Means are provided for moving it to or from the bottom plate. The whole arrangement is enclosed air-tight in a glass jar.

The first experiment with the apparatus would be this. Raise the lower plate to a high potential, say 100 volts. Having discharged the electrometer, by connecting it to the earth by a wire, let the connection be removed. The electrometer will now receive a charge, and its deflection will increase

rapidly; for electricity is leaking, under the influence of the radio-active substance, from the highly charged lower plate to the upper one, which is connected to the electrometer, and which was initially uncharged. The upper plate thus receives a charge, and the electrometer indicates it. It makes no difference

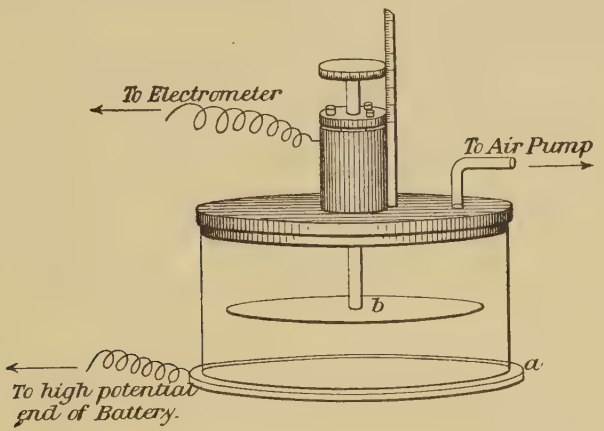


FIG. 21.—Parallel plate arrangement for investigating electrical conduction under Becquerel rays. The bottom plate, *a*, on which the radio-active substance is spread, is kept at any desired high potential. The upper plate, *b*, is movable, and parallel to the first. The distance can be altered and measured by the micrometer screw. A stuffing box provides for air-tightness. The top cover of the glass jar is of ebonite to provide for insulation.

whether the bottom plate was charged positively or negatively. A positive charge can leak across the space between the plates just as well as a negative one. Now let the air be exhausted from the bell jar by means of a good air-pump. We shall find that the electrical leakage has disappeared. No charge now reaches the upper plate.[1]

It is evident, therefore, that the true interpretation of the electrical leakage effect is that the Becquerel rays are able to make the air through

[1] It will be remembered that the radio-active substance is constantly firing off negatively charged corpuscles; these are no doubt conveying negative electricity to the upper plate. But under ordinary conditions their effect would be too small to be noticeable with this apparatus.

which they pass a conductor of electricity; in the absence of air no leakage takes place.

Let us now suppose the air readmitted to the vessel, in order to investigate the leakage effect in another way. The question to be tested is this. What is the relation between the current of electricity flowing between the plates and the electric pressure which causes it to flow? In technical language, What is the relation between the current and the electro-motive force?

In the most familiar case of electrical conduction—the conduction of electricity along a metal wire—the relation between the current and the electro-motive force is the simplest that can be imagined. For the current along the wire is simply in proportion to the electric pressure which is applied to its ends. If the electric pressure is doubled, the current is doubled also. If the electric pressure is increased a thousand times, the same is true of the current; that is, provided that the wire is not allowed to get hot—a condition which prevents our testing the law beyond a certain point. But so far as the wire can be kept at a constant temperature, the law, which is known as Ohm's law, is rigorously and exactly true.

The question then is, Does the air made conducting by Becquerel rays behave like the metal wire? Both of them are conductive of electricity. May not both behave alike?

It is a question for experiment, and the answer which experiment gives is that they do not.

We can vary the potential or electric pressure of the lower plate by connecting it to the high potential end of an electric battery. The number of cells included in the battery can be varied at pleasure. Each successive cell increases the potential by a definite amount, according to the construction of the cell. If

we try one cell, and measure the leakage current, we shall get a certain value for it. If we use two cells, we shall get nearly twice as much, and, perhaps, with three, not far from three times as much as with one. But this state of things will not continue much further. It will soon be found that the addition of battery cells does not increase the current so much as at first; and when a certain number of cells has been added, the current will have reached a limit. A further addition of cells will not increase it at all, or, at least, not to any measurable extent. The greatest current which can be got through the air is called the saturation current.

The number of cells required to produce saturation of the current depends on the conditions of the experiment—the distance between the plates, and still more the strength of the Becquerel rays. But to give some idea, we may say that, with uranium nitrate, and with the plates an inch apart, 100 volts difference of electric pressure between the plates would be amply sufficient. This is a very ordinary value for the electric pressure used in domestic electric lighting.

A theory has been developed which gives a very satisfactory explanation of the existence of the saturation current. Before examining the experimental facts further, it will be well to give an account of this theory. For we shall then be able to see their true bearing, instead of having to content ourselves with recording them empirically.

It has now for many years been recognised that when a current of electricity passes through a liquid such as dilute sulphuric acid or salt and water, the process consists in the motion of positively charged particles up to the negative electrode, and negatively charged ones up to the positive, under the influence

of electric attraction. The particles are called ions; and there is every reason to believe that such a solution partially decomposes of its own accord into ions, so that they are ready, when the electric force is applied, to move up to the electrodes, thus conveying a current through the liquid.

With air in its ordinary state it is otherwise, for under such circumstances it contains no ions, or practically none, and cannot convey an electric current. But the Becquerel rays are able to decompose it into ions. Each atom of the α-rays, or each corpuscle of the β-rays, sooner or later strikes one of the molecules of the air. The molecule is shattered by the blow, and it breaks up into two ions, one possessing a charge of positive electricity, the other an equal charge of negative. When these ions were joined to form a molecule, their charges served to hold them together; and the charges neutralised one another so far as any external matter was concerned. For the molecule contained as much positive electricity as negative, and so, taken altogether, it was free from electrification, and would not move under the influence of electric force. But now that the ions constituting the molecule have been separated, they are attracted by the electrodes, and move up to them. It must be noticed, however, that the positive ions are also attracted by the negative ones, and if there are plenty of both in the gas, pairs of them are sure to come into contact, and unite again to form neutral molecules. If no external electric force is acting, all the ions will do this sooner or later, and the state of things will then be the same as at first, if the radio-active substance is taken away. Of course, if it remains, more ions are constantly brought into being, and those again recombine. The formation of ions in a gas is called the ionisation of the

gas. Thus in air exposed to the Becquerel rays there is a constant ionisation in progress. As the number of ions increases, the chance of a positive ion meeting a negative one, and pairing with it, of course becomes greater; so that the rate of recombination becomes greater. At last the rate at which the ions recombine becomes equal to the rate at which they are produced, so the supply reaches a stationary value. This is practically attained in a fraction of a minute after the rays begin acting.

Let us now consider what happens when an electric force acts on the ions. They move across to the electrodes, and are thus removed from the sphere of action. If they move very slowly, most of them will meet with partners on the way, and will be no longer effective as carriers of electricity. A few of the ions, however, are able to get across without recombining. These few are the carriers of the current, which is accordingly small. Now let double the electric force be applied. The ions will move twice as fast as before.[1]

Accordingly they will have only half the chance of meeting partners before they get across, and consequently nearly twice as many will get across uncombined. But this will continue true only for small electric forces, because when large forces are applied and the ions move fast, a large proportion of the total number will get across uncombined; and then it is evident that doubling the electric force cannot double the number of ions that get across uncombined, for there are not enough ions altogether to allow of that.

The most that can be done is to apply an electric force large enough to snatch practically all the ions away as soon as they are formed, giving them no time

[1] It will be understood that the velocity is steady, and does not increase, owing to the resistance of the air.

to recombine. In that case, all the ions are utilised in conveying the current, and the current is as large as it can be. Nothing is gained by snatching the ions away faster still by a larger electric force. So the current has reached a limit independent of the electric force. All this, it will be observed, is in exact agreement with what was found experimentally to occur.

If a saturating electro-motive force be used, it is found that the current between the two plates of our apparatus *increases* instead of diminishing when the plates are put further apart. This seems a very strange result when we compare it with what happens when electricity is flowing through a metal; for the less distance the current has to flow through a metal the larger the current will be.

But the theory of ionisation affords a ready explanation. For the further separated the plates are, the more ions are formed in the air between them, and, as the saturation current uses up all the ions, this current is naturally increased.

The α-rays are readily absorbed by the air, as we know; so that if the distance between the plates is considerable, the rays which reach the air near the top plate will be much weakened by absorption, and the air there will not be nearly so strongly ionised as the air near the radio-active substance.

Now in most cases the ionisation due to α-rays greatly exceeds that due to the other varieties, so that if the plates are separated so far that the α-rays do not extend to the top plate appreciably, we shall not get many more ions produced between the plates by separating them still further. This anticipation, again, is confirmed by experiment; for it is found that the saturation current does not increase beyond a certain point when the plates are widely separated.

It is interesting to inquire what happens when the air pressure is altered. Let us suppose the plates well separated—say two inches. When there is no air, no ions can be produced, and there will be no current. If now the air be admitted to a very feeble pressure, say $\frac{1}{100}$th part of the atmosphere, the α-particles will have very few chances of meeting molecules of the gas, so as to ionise them. But some collisions do occur, and accordingly a few ions are produced, and a feeble current will pass. The number of collisions is not, however, sufficient to impede the α-particles to any serious extent.

If the air pressure be made twice as great, nearly twice as many ionising collisions will occur, but not quite twice as many, for the particles, after passing through the first half of the gas, are now moving a little more slowly, and are to some extent like a spent bullet. Thus they will not be so well able to ionise a molecule, if they do not hit it fairly, or, perhaps, a few of them will have been stopped altogether, and will therefore no longer be able to produce ions at all. So that, with the doubled air pressure, we cannot expect the current to be quite double; but it will not be much less. This point, like a very similar one we had to deal with in considering the recombination of ions, may be a little difficult to follow at first; but with consideration it will become quite clear.

The ionisation, and consequently the current, must then be proportional to the pressure when the pressure is small. Consider now the case when the pressure is so large that the rays are altogether absorbed in the space between the plates. It will be evident that in this case all the α-particles are used up in making ions; and no more ions can, under any circumstances, be produced by the rays. So the current has reached a maximum, and to increase

the pressure still more cannot increase it. All this is entirely confirmed by experiment.

Everything that we have said will apply equally to the α- and β-rays, and probably to the γ-rays also. In the case of the more penetrating kinds of rays, however, the pressure at which the saturation current would reach a maximum would be very great.

It will be convenient to sum up the conclusions of this somewhat difficult argument.

The leakage of electricity under the Becquerel rays can be accounted for by the theory that the impact of the projected particles on the molecules of the air break them up into charged ions. For every ion carrying a positive charge, another is formed carrying a negative one. The convection of the electric charge under the influence of the electro-motive force constitutes the observed electric current. The ions when left to themselves recombine to form neutral molecules.

This theory accounts for the following facts. The current is proportional to the electro-motive force when the electro-motive force is small. When the electro-motive force is large, the current reaches a maximum, or is said to be saturated. The saturation current increases with the distance between the electrodes. When the distance between the electrodes is fixed, the saturation current is, for small air pressures, proportional to the pressure. For large air pressures, it reaches a maximum, independent of further increase in the pressure.

Many experiments have been made on the properties of the ions. We cannot enter into the details of these, but the main conclusions must be indicated.

The charge on the ions has been determined by the same method that was found effective for the

corpuscles emitted by metals under the influence of ultra-violet light.[1] The result is to show that they too carry the same charge as the hydrogen atom in the electrolysis of liquids. It might perhaps be at first concluded that the ions were identical with the cathodic corpuscles. This view, however, cannot be unreservedly accepted. For the velocity of the ions moving through air under an electro-motive force is very small. They do not move more than about one centimetre per second, if the potential gradient is one volt per centimetre. This has been ascertained by making them move against an air blast, and adjusting the blast so that they just could not make headway against it, and convey an electric current in the opposite direction, or by equivalent methods. Now this velocity is much smaller than the velocity which an atom would acquire if pulled through air under an equal force. We must conclude that the ion, so far from being smaller than an atom, is much larger. The most probable view is that the negative ion consists of a corpuscle which has attracted to itself a number of other uncharged atoms; these impede its motion. The positive ion consists of a positively charged atom, also with attendant uncharged atoms.

The rate of recombination of the ions has been studied by blowing the ionised air away from the radio-active substance at a known velocity, and determining the amount of conductivity at different distances along the tube. Recombination is in most ordinary cases practically complete after two seconds. For it is found that two seconds after the air has left the radio-active substance, its conducting power has practically vanished.

Hitherto we have alone considered the ionisation

[1] Chap. i. p. 14.

of air by the rays. Some attention must now be devoted to other gases.

The general phenomena are in all respects similar to those already described for air. The point which requires special consideration is the comparison between the amount of ionisation in air and in other gases. We wish to compare the gases when they are under the influence of rays of the same strength throughout. To secure this, it is necessary that the absorption of the rays by the layer of gas used shall be small; for otherwise the first layers of the gas will appreciably screen the further layers from the radiation to an unknown extent. This prevents accurate comparisons being made.

To secure practical uniformity of the rays throughout the gas, it is necessary to select a pressure within that range for which the ionisation is proportional to the pressure. Otherwise the conditions of the experiment become very complicated, and the results difficult to interpret.

For the α-rays it is necessary to select some quite low pressure, say $\frac{1}{20}$th of the atmospheric pressure, for the experiment. The apparatus with parallel plates already described is very suitable for the purpose. It should be set with the plates, say, $\frac{3}{8}$-inch apart. Polonium may be conveniently employed as the radio-active substance, since it gives α-rays only. The various gases, hydrogen, carbonic acid, etc., are introduced into the glass jar, from which the air has been previously removed by an air pump. Each gas is in turn admitted to the apparatus, to a pressure of $\frac{1}{20}$th of an atmosphere, and the saturation current measured. Atmospheric air serves as a convenient standard with which to compare the other gases. The radio-active substance must not be disturbed throughout the series of experiments, or they

will no longer be strictly comparable with each other.

In experimenting with the β- and γ-rays, it is not necessary to work at reduced pressure; for these rays are not much absorbed by a reasonable thickness of gas. In these cases it is more convenient to modify the apparatus. The bottom plate should be made thin, and the radio-active substance placed on a flat dish, which is placed underneath the apparatus, outside it. The rays then penetrate the bottom plate and act on the gas between the plates. In examining the γ-rays, a thick slab of lead must be interposed between the radium and the bottom plate.

Experiments made on the lines described have shown that all three kinds of rays give nearly the same results; for it is found that the ionisation of a gas is in each case nearly proportional to its density. Sulphurous acid, for instance, which is rather more than twice as heavy as air, is also rather more than twice as much ionised, other things being equal.

The law is only roughly true; the most notable exception is hydrogen. This gas is more than twice as much ionised by all the varieties of rays as it ought to be, if the relation between ionisation and density were exact. There are other exceptions, but these are comparatively unimportant. The β- and γ-rays seem to give exactly the same results, as nearly as the experiments can show. The α-rays give slightly, but still distinctly, different values. The general relation between ionisation and density holds good for all the varieties of rays; but the exceptions to it are not always the same.

The resemblance between the laws connecting absorption and density, and on the other hand ionisation and density, cannot fail to attract notice. If both

ionisation and absorption are proportional to density, they must also be proportional to one another.

Ionisation by the α- and β-rays is regarded as due to the impact of projected particles on the molecules of the gas. This leads very simply to an explanation of the connection between ionisation and absorption. Every particle stopped by impact with molecules produces a certain number of ions. Thus the number of ions produced is proportional to the number of particles stopped. In other words, ionisation is proportional to absorption.

Since ionisation is proportional to absorption, the same amount of ionisation should always attend complete absorption, whatever the gas in which the absorption takes place. This affords a very direct experimental test of the truth of the relation. It is not difficult to completely absorb the α-rays in a moderate thickness of gas, and to measure the resulting ionisation. Professor Rutherford made experiments of this kind early in the history of the development of the subject; he found that the ionisation was, at any rate nearly, the same whatever gas was used to completely absorb the rays. This is a very satisfactory confirmation of the theory that ionisation is proportional to absorption.

Hitherto the ionisation of gases has alone been considered; but we have seen that the law of absorption and density is not at all confined to gases. It holds approximately true for all classes of substances, solids and liquids as well as gases. Is it natural to inquire whether the law for ionisation does the same?

It is probable that this is the case; but we do not know for certain, for there are formidable difficulties in the way of measuring the ionisation of liquids and solids.

We can show that some liquids, at all events, are

ionised by the Becquerel rays. It would be of no use to try to observe the ionisation of water. For it is impossible in practice to get water absolutely free from saline impurities; and the faintest trace of such are sufficient to give it an enormous conductivity, compared with anything that the Becquerel rays could do. The effect of these would be lost in the large conductivity already existent. To try to detect the extra conduction due to them would be like trying to see the rise of level of the water in a pond when an extra thimbleful was emptied into it.

The only kind of liquids which it is of any use to try are those which conduct electricity but very little, if at all. Examples of such liquids are liquid air, bisulphide of carbon, benzene, and petroleum ether, such as is used in the propulsion of motor cars. M. Curie has experimented on the ionisation of such liquids by the rays. He was able to detect conductivity. The way he carried out the experiments was practically equivalent to what has been described for gases, but the space between the electrodes was filled with a liquid instead of a gas.

The relation between current and electro-motive force was investigated, just as for gases. It was not found practicable to apply a large enough electro-motive force to produce saturation, though some signs were observed that saturation was being approached.

There is no reason to be surprised that saturation is difficult to attain in a liquid; for it is natural that the ions should encounter great resistance in penetrating so dense a medium. They will therefore move very slowly under the electro-motive force, and a very large electro-motive force will be necessary to draw them away so quickly that none of them have time to recombine. In other words, a very large

electro-motive force will be necessary to produce saturation.

As the saturation current has not been measured, we have no precise information as to the ionisation of liquids by the rays, and whether it is proportional to the absorption.

With regard to the ionisation of solids, our information is still more scanty. M. Becquerel found that paraffin wax conducted to some slight extent under the influence of the rays. This conduction persisted for a long time after the radio-active substance had been removed. The paraffin only slowly recovered its usual insulating properties.

Probably some kinds of glass also conduct to a certain extent. Radium may often be kept for months sealed up hermetically in a glass tube. Now negative corpuscles are constantly being shot through the glass. If the positive charge which remains on the radium were not able to escape by conduction, it scarcely seems possible that the glass could ever stand the electric stress for more than a few hours without being pierced. Puncture does sometimes occur.

It is not difficult to understand that in a solid substance the ions produced by the rays may not be free to move except with great difficulty under electro-motive force. If this is the case, the current can be conveyed, and we cannot measure the amount of ionisation produced.

Conduction of electricity by metals is now generally regarded as due to a process analogous to the motion of ions in an electrolyte, or in an ionised gas. If this is really so, some kind of ions must exist in a metal which are free to move through the metal. It is hardly possible that these ions should be of the same kind as the ions produced by Becquerel rays

in gases; for the latter are, as we shall see, large compared with molecules, and cannot be supposed to move through a solid. Still, it is conceivable that the rays produce some extra conduction in metals. There would, however, be no chance of detecting it, in presence of the enormous conduction already present.

It is now time to return to a matter which was left over. This is the behaviour of the γ-rays with regard to ionisation and absorption.

These rays, it will be remembered, are of doubtful nature. It is uncertain whether they consist of corpuscles or of Rontgen rays generated by the stoppage of corpuscles. Now the Rontgen rays emitted by a vacuum tube are able to ionise gases, just as the Becquerel rays do. How or why they do this is not known; for the simple explanation available in the case of the α- and β-rays of radium is not available. The Rontgen rays are believed to be of the nature of electro-magnetic waves or pulses, and it is not apparent why such a wave should be able to separate the ions in a molecule.[1] But whatever the reason, it is a fact that the Rontgen rays do produce ionisation of the same order of intensity as the ionisation produced by radio-active substances; moreover, there is every reason to conclude that the ions are of the same nature in each case. When we come to compare the ionisation of different gases, however, an extraordinary difference between the two ionising agents makes its appearance. For it is found that different gases are not ionised by the Rontgen rays

[1] It is true that there is an electric field in the wave front which might be conceived capable of tearing the ions apart. We do not know the strength of this field, but it is difficult to believe that it can be strong enough to produce such a result. Moreover, it is not clear why so few of the molecules encountered by the wave are ionised, or what there is to distinguish the molecules which do get ionised from those which do not.

in anything like the same ratio as by the Becquerel rays. The law of densities is not at all obeyed.

It is with gases or vapours containing elements of high atomic weight that the difference is most conspicuous. Let us give an example. Iodine has a high atomic weight—one hundred and twenty-seven times that of hydrogen. Methyl iodide, a compound containing it, gives off a vapour about five times as dense as the air. It is accordingly about five times as much ionised by the Becquerel rays. But when we come to try the effect of the Rontgen rays, the ionisation of methyl iodide is no less than seventy times the ionisation of air.

A corresponding difference appears in the absorption of the two kinds of rays by solids. Substances of high atomic weight absorb much more in proportion. Platinum is about twenty-one times as dense as water, and a sheet of platinum would absorb the Becquerel rays to about the same extent as a stratum of water twenty-one times as thick. But with Rontgen rays, the absorption by such a sheet of water would be quite inconspicuous in comparison with the platinum sheet.

A simple illustration of the same thing has already been encountered in the second chapter. It was mentioned that when the shadow of the hand was observed on a fluorescent screen by means of the Rontgen rays, the bones were clearly visible, for they gave a much darker shadow than the flesh; but with radium to illuminate the fluorescent screen, the difference between flesh and bone was much less conspicuous. The reason is that bone, which consists mainly of calcium phosphate, is made up of elements of much higher atomic weight than flesh, of which the elementary constituents are oxygen, hydrogen, nitrogen, and carbon; accordingly, though the bone

and flesh are about equally opaque to Becquerel rays, the bone is far more opaque to Rontgen rays than the flesh. The result is that they are seen in sharp contrast, and the bones are clearly visible.

It has been explained that in regard to relative ionisation and absorption, the γ-rays of radium behave just like the α- and β-rays, and thus absolutely unlike ordinary Rontgen rays. This fact seems to be a strong argument against the theory that identifies them with Rontgen rays, and to be favourable to the view which considers them to be an extreme kind of β-rays.

Rontgen rays are of different kinds, for the rays obtained from a highly exhausted vessel are much more penetrating than those from one less perfectly exhausted. There is reason to think that the relative ionisations of gases under Rontgen rays vary with the quality of the rays. It is difficult, if indeed at all practicable, to obtain Rontgen rays as penetrating as the γ-rays of radium, and the relative ionisations under such rays have not yet been measured. But Mr. Eve has recently made measurements which indicate that the most penetrating Rontgen rays he was able to obtain approach nearly in their properties to the γ-rays. This clears away the principal outstanding difficulty in admitting that the γ-rays are Rontgen rays.

CHAPTER V

THE CHANGES OCCURRING IN RADIO-ACTIVE BODIES

If a specimen of radium bromide is placed in a glass tube, and gently heated, it will be found that a small quantity of gas can be extracted from it, which has most remarkable properties. The gas has, in fact, all the peculiarities of radium itself; for, if collected in a glass tube, it will emit the Becquerel rays. A fluorescent screen brought near it will light up, and, indeed, the tube itself is sufficiently fluorescent under the influence of the rays to be easily visible in the dark. The air outside the tube is rendered conducting by the rays emitted. Photographic plates are acted upon. The glass of the containing tube is turned perceptibly violet even in twenty-four hours. In short, all the characteristic phenomena are obtained. This radio-active gas has become known as the radium emanation.

The volume of emanation emitted by any such quantity of radium as is at present procurable, is absolutely infinitesimal. From 50 milligrammes of radium bromide (of which the market price would be about £25-£30) the volume of emanation procurable at any one time probably would not exceed that of a large pin's head, if, indeed, it amounted to so much. But the gas is so active that, if it was mixed with a million million times its own volume of air, the electrical leakage through a sample of the mixture, due to the action of the radio-active emanation on the air containing it, would be quite conspicuous.

It is only with great difficulty, and by taking very special precautions, that the emanation can be obtained in the pure state. But, for examining many of its properties, that is by no means necessary. The admixture of another gas, such as ordinary air, does not at all interfere with many of the experiments. In some cases, in fact, it facilitates them.

We have spoken of heating the solid radium bromide. But the same result can be obtained by dissolving it in water. The solution then gives off the emanation. A mixture of oxygen and hydrogen in their combining proportions is also given off, as we have already seen. This mixture serves to wash out the emanation, and the mixture may be extracted and collected by means of a Sprengel air-pump.

A mixture of the emanation with air may readily be obtained by bubbling air through the solution. If this air be led into a tube containing some zinc sulphide, the fluorescence of the sulphide will be very brilliant.

The electrical effects due to the emanation may easily be shown. Air which has been bubbled through radium bromide solution will rapidly discharge the electroscope when blown on to it, or better, admitted into the case of the instrument so as to surround the gold leaves.

Air which contains the emanation behaves in all respects like air which is exposed to radium; but it is able to keep itself constantly ionised by the radio-active material which it contains; whereas the ionisation of ordinary air only continues as long as the radium acts upon it. If the radium is withdrawn, the conducting power disappears in the course of one or two minutes, owing to recombination of the ions already present, and the failure of the supply of new ones. If the electro-motive force is acting all

the time, the ions are used up immediately, and the phenomena cease the moment the radium is withdrawn.

The emanation behaves like other gases in one very important property. It can be condensed to the liquid or solid form by cooling. Different gases differ very greatly in this respect. Steam or water vapour, for instance, can be almost completely condensed out of a space which contains it by means of ice, though to remove absolutely all perceptible traces of it would require a lower temperature still.

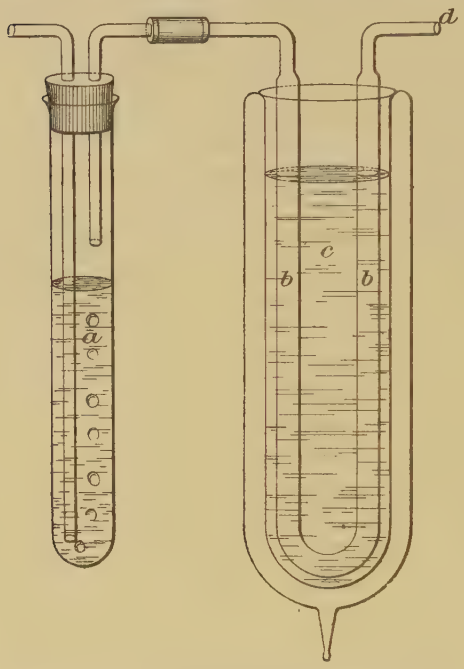


FIG. 22.—Arrangement for condensation of the emanation by liquid air. *a* is a solution of radium bromide, which yields the emanation. Air is bubbled through it, and carries the emanation through to the U tube, *b*, immersed in liquid air, where it is condensed. The liquid air is contained in a double walled vessel, *c*, with a vacuum between the walls. This serves to prevent the access of heat. While *b* is surrounded by liquid air, no emanation can escape through *d*, and it has lost all discharging power. When the liquid air is removed, the accumulated emanation evaporates, and the issuing air is strongly radio-active.

To condense the emanation completely, it is necessary to make use of the much greater cold which we can command by the use of liquid air.

The condensation can be shown in the following way. Air bubbled through the solution of radium bromide is passed through a U-shaped glass tube, immersed in liquid air (Fig. 22). This cools it to the temperature of the liquid. At that temperature the emanation no longer remains a gas, but separates out

in the solid form, and is deposited on the walls of the U tube. The whole process may be watched in the dark. The air charged with emanation causes visible fluorescence in the glass tubes. But the fluorescence does not extend beyond the cooled portion of the U tube when it condenses. The accumulated emanation condensed in the tube shows a brilliant fluorescence, proving, incidentally, that even at this low temperature it is still able to emit Becquerel rays.

The condensation of the emanation can be shown even more effectively by another experiment. The emanation, with as little admixture of any other gas as possible, is introduced into a glass globe (Fig. 23) containing zinc sulphide, which fluoresces brilliantly under its influence. Communicating with the globe by a short tube is another small bulb which can be immersed in liquid air. As soon as this is done, all the emanation condenses in the bulb, so that there is none left in the large globe, and the zinc sulphide is no longer luminous. If the bulb is removed from the liquid air, the emanation evaporates again, and the luminosity is restored.

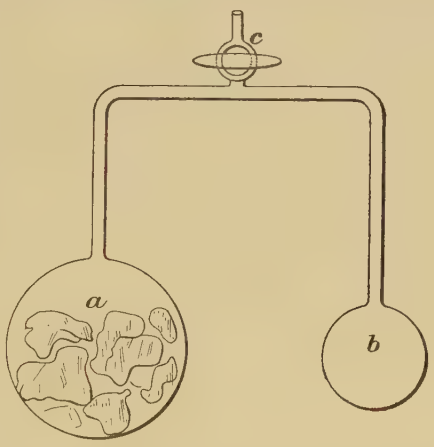


FIG. 23.—Arrangement for showing the condensation of the emanation. An inverted U-shaped tube carries at each end a glass bulb. The larger bulb, *a*, contains zinc sulphide or other fluorescent materials. The arrangement is exhausted of air, and the emanation introduced through the stopcock, *c*, which is then closed. The zinc sulphide glows brilliantly. On immersing *b* in liquid air, the emanation all condenses, and *a* loses its luminosity. When *b* is allowed to heat up again, the luminosity is restored.

The emanation seems to be absolutely unaffected by any chemical treatment that we can submit it to. Not even the most violent treatment, such as passing

it over red-hot magnesium, alters its radio-activity in the slightest. The only other known gases which can withstand such treatment are the inert constituents of the atmosphere, which have been discovered of recent years, helium, neon, argon, krypton, and xenon. Any other gas, such as oxygen, carbonic acid, or even nitrogen (which is generally very inert), enters into chemical combination with red-hot magnesium. In its chemical properties, or rather want of properties, then, the emanation resembles the inert gases.

We have not yet any very satisfactory means of determining with accuracy the density of the emanation. As we have already remarked, the volume of pure emanation obtainable does not exceed that of a pin's head, and it will readily be admitted that to attempt to weigh such a quantity of gas would not be a very hopeful task. Sir William Ramsay and Dr. Travers succeeded in determining the density of xenon with only 7 cc. of gas, equivalent in English measure to about half a cubic inch. This was justly regarded as a triumph of experimental skill. But even that degree of refinement is of course utterly insufficient for dealing with the emanation. There is, however, a means by which we can obtain some approximation to the desired result. It depends on the diffusion of the emanation through a porous plate.

Let us take a vessel made of porous (unglazed) earthenware, such as is used for a Daniell's battery, and fill it with carbonic acid gas, closing the mouth air tight. After a little time we shall find that there is less carbonic acid in the vessel than there was at first. Some of it has diffused out through the porous walls. How fast it has diffused out will, of course, depend on how thick the porous vessel which we have

chosen for the experiment may happen to be. But we shall find that, however much or little carbonic acid there may have been to begin with, the time which elapses before half of that amount has escaped will always be about the same. Suppose, for instance, that there was one gramme of carbonic acid by weight to begin with. We can find by experiment how long a time elapses before half that quantity has escaped. Suppose we found that it took an hour. Then after another hour we should find that the quantity had been halved again. There would then be only a quarter gramme; and so on. Whether there was air mixed with the carbonic acid to begin with is quite unimportant. The only thing we need consider is the amount of carbonic acid inside. It is essential that the carbonic acid should not be allowed to accumulate outside, or some of it would diffuse back to the inside again. But if the porous vessel is exposed to the air of the room, the carbonic acid which gets out is sure to be blown away effectually by chance draughts.

Now, let us try the same thing with another gas, hydrogen. We shall find that the hydrogen, which is much lighter than carbonic acid, gets away much faster from the same vessel. In fact, it is found that the rate at which gases diffuse depends only on their density. A dense gas always diffuses more slowly than a light one.[1]

Now it will be seen that this method is admirably adapted to the case with which we are concerned. For, as we have said, the admixture with air does not affect the rate of diffusion. All that we have to do is to find the rate at which the emanation escapes through a porous vessel, whose behaviour

[1] The quantitative law is that the rates of diffusion are inversely proportional to the square roots of the densities.

with gases of known density has been found. We can arrange to measure the quantity of emanation in the porous vessel at any moment by observing the rate of leak of electricity through it. The absolute quantity present, which is so difficult to measure, does not at all concern us. All we want is a uniform scale of measurement which is consistent with itself. We measure the rate of leak due to the emanation from time to time, and find how long a time elapses before it falls to half its initial value. We are then in a position to compare its density with those of the other gases.

Experiments made in this way are not susceptible of any high degree of accuracy, but they point to the conclusion that the emanation is about ninety times as dense as hydrogen, or more than six times as dense as air. This number must be accepted with some reserve. But there is no doubt, at all events, that the emanation is, for a gas, exceedingly heavy.

The density of a gas is a very important datum. For every gas, observed under similar conditions, is equally coarse grained. Each gas contains the same number of ultimate particles or molecules in the same volume. So that the weights of the molecules are in the same ratio as the weights of equal volumes, or, in other words, as the densities. By comparing the densities, we can compare the weights of the molecules. The molecule of the emanation is, then, apparently about ninety times as heavy as the molecule of hydrogen.

Unlike the radium salt which furnished it, the emanation becomes perceptibly less active every day, until the activity has become so small that it is no longer perceptible. The activity is found to decay every day by a fixed percentage of the amount which it possessed at the beginning of that day. It

goes down by about one-fifth of its value every day. This is nearly analogous to the way in which a sum of money invested at compound interest increases. But, to make the analogy exact, we must suppose the interest to be subtracted from the capital, instead of being added to it. In that case the capital would diminish in exactly the same kind of way that the emanation diminishes in activity when left to itself. We have already met with the same law in considering the diffusion of gas out of a porous vessel. The rate of decay of the emanation is conveniently indicated by saying how long it would take to diminish to one-half its initial activity. Careful experiments have shown that the time required is 3·7 days.

It is a very remarkable fact that the rate of decay of the emanation is absolutely independent of the circumstances in which it may be. Hot or cold, solid or gaseous, concentrated, or diluted with air, it makes no difference whatever. We may condense the emanation with liquid air, and keep it condensed for some days. But it will be found that when we let it evaporate again, it has diminished in activity just so much and no more as it would have if it had been left in the gaseous condition all the time. If we start with a strong emanation, there will be no difficulty in still recognising its presence after the lapse of two months.

Sir William Ramsay and Mr. Soddy have recently obtained the pure emanation, and have measured its volume, by the use of a tube of very narrow bore, and by working at a pressure much less than that of the atmosphere. They have observed that the volume contracts till no longer measurable, and that this diminution follows the same law as the radio-activity; the volume reaches half its initial value in 3·7 days. It is clear from this experiment

that the gaseous emanation is slowly turning into solid products, which occupy a volume very small compared with its own. The experimental difficulties of this observation are very great, and the results, as might be expected, not free from apparent anomalies; but there can be little doubt of the general conclusion.

We must now return to the radium salt, and consider its behaviour after the emanation has been taken from it. As the emanation is so very radioactive, it will be readily understood that, while still with the radium, it contributed a good deal to the activity of the latter. So that the radium, deprived of its emanation, is much less active than it was before. But this enfeeblement does not last. If the radium is tested from day to day, it is found to be slowly becoming more active again. In fact, it is brewing fresh emanation. It will be remembered, however, that the emanation does not last. So that there is a limit reached, when the emanation dies away as fast as the radium can make more of it. After that the activity of the radium will not increase any further. This state of things is practically reached after about a month.

The radium salt is not able to retain the whole of its emanation, even at ordinary temperatures. A little of it is always diffusing away.

The same behaviour can be traced when the radium salt, instead of being heated, is dissolved in water. This equally separates the emanation, which comes away when the water is dried off. The salt recovered from the solution is enfeebled like that which has been heated, and the activity comes back in exactly the same way.

We have seen that radium constantly generates the emanation. It may be asked, Does the emanation

in its turn generate anything else? The answer is that it does.

The emanation, as we have seen, is only obtainable in sufficient quantity to occupy a just visible volume, and that notwithstanding that it is gaseous, and consequently occupies a far larger volume weight for weight than a liquid or solid would do. When we state, therefore, that the substance which the emanation generates is a solid, it will not be surprising that no quantity large enough to be visible at all, even under the microscope, has yet been accumulated. If it is not visible, how can we be sure that it exists at all? The answer is, By its radio-activity, which is exceedingly strong.

The solid substance, generated by the emanation, has been called, not perhaps very happily, the induced or deposited activity. This name was given before the material nature of the deposit had been recognised. Professor Rutherford has proposed the name emanation *X*—the unknown substance from the emanation. This name, too, seems to leave something to be desired, from a literary point of view. In the present work the substance will be called the active deposit.

To demonstrate its formation, introduce a rod or plate of any material into a vessel containing the emanation (mixed, of course, with air), and leave it there for a few hours. If the rod is withdrawn after that time it will be found to be quite radio-active when tested by the electroscope. A layer of the active deposit, so thin as to be invisible and unweighable, has encrusted it. We can scrape off this layer of deposited activity by means of emery paper. The activity will then remain in the dust left by the scraping process, or we can induce it to evaporate or rather to sublime, if we make the surface on which it is deposited intensely hot.

A curious peculiarity of the deposited activity is that it deposits much more easily on a negatively charged surface than on one that is positively charged. It is evident, therefore, that the particles of this substance, as they are formed throughout the volume of the gaseous emanation, are charged with positive electricity. This positive charge induces them to move up to the negatively charged wire, since opposite kinds of electricity attract one another. When the emanation is allowed to remain in the radium salt, it generates the deposited activity in the salt, and this deposited activity, as well as the activity due to the emanation, contributes to the activity of the radium. The activity of a radium salt which has not recently been deprived of its emanation, accordingly consists of three parts. One of these parts is contributed by the radium itself, which emits Becquerel rays, while changing into the emanation. A second part is due to the emanation, while changing into the active deposit, and a third part is due to the active deposit itself.

It will be remembered that radium yields three kinds of rays. The α-rays, consisting of particles of atomic dimensions positively charged. The β-rays, consisting of negative electrons, and the γ-rays, of great penetrating power, which are probably Rontgen rays generated by the β-rays. Does each of the three constituents of ordinary radium—radium itself, its occluded emanation, and the active deposit—give off all three kinds of rays, or is each of them responsible for one kind? This question has been put to the test of experiment. It is found that neither of these alternatives represents the truth. For the radium itself, when freed from the other products, gives only the α-rays. Its radiation is completely stopped by the thinnest screen of solid material.

The same is true of the emanation. The active deposit is responsible for the whole of the β- and γ-rays. It contributes a part of the α-rays also.

In the present state of our subject, we can give no further interpretation to these facts. But there can be no doubt that, with the progress of knowledge, their true bearing will become clear.

When describing the emanation, we stated that its activity was apparent outside the glass tube containing it. That is the superficial appearance of the phenomenon. But we have now seen that the penetrating rays, which alone can produce effects outside the tube, are exclusively due to the active deposit. It is really this latter, deposited on the inside walls of the tube, which enables the activity to be observed outside. By measuring the activity of the rays outside by the electrical method, we can follow the development of the active deposit. When the emanation has just been put in, no outside effect is obtained. The outside effect gradually increases in strength, but more and more slowly until a limit is reached. This limit is attained in a few hours. It represents the stage at which the active deposit loses as much by its own decay, which we shall describe immediately, as it gains by the development of fresh supplies from the emanation.

The active deposit, like the emanation, is an unstable substance. It loses its power much more quickly than the emanation does. For in a few hours after its formation it is no longer radio-active.

The changes which occur in the active deposit are very complex, in contrast to the change in the emanation. For while the emanation dies away uniformly at a rate which is proportional to the amount present, the active deposit behaves in quite an eccentric manner. It begins to decay quite fast.

After some ten minutes this decay stops, and the activity remains stationary for a time. Then it starts decaying again, and goes on doing so till no longer perceptible. It is evident that the change takes place in several stages, each occurring at a characteristic rate.

To analyse the experimental results, so as to find out the number of changes which occur, and the rate at which each proceeds, is not a very easy matter. For it is not as if each change was quite over before the next one began. In that case the problem would be one of comparative simplicity. But unfortunately the changes overlap: when a portion of the deposit has undergone its first change, this portion will proceed to the second change, while the remainder goes on with the first one; and so on with the other changes. Professor Rutherford, to whom, with Mr. Soddy, we owe most of our knowledge concerning the processes which occur in radioactive bodies, has lately succeeded in specifying a series of changes which will explain very satisfactorily the observed phenomena. It is not proposed here to enter on the considerations which led him to this result, for they are only of technical interest. The result itself, however, is of great importance. The changes are three in number.

(1) A change which destroys half of the original deposit in three minutes.

(2) A second change, in which half the material changes in thirty-six minutes. During this change, no rays are given out; the material is, however, preparing to get into the third stage.

(3) A third stage in which half the matter changes in twenty-eight minutes.

After the third stage there is still a slight activity left. This is exceedingly small, and only amounts to

about $\frac{1}{20000}$ of the initial amount. But, on the other hand, it seems to be quite permanent, so far as the experiments hitherto made have shown. We do not yet know very much of the properties of this last kind of activity, but it gives all three kinds of rays.

We have considered the successive changes which occur in radium, the production of the emanation, its change into the active deposit, and the changes of the activity of the latter.

We now turn to the changes in the other radio-active elements—uranium, thorium, actinium, and polonium. The case of uranium is peculiarly interesting, on account of its simplicity. For it only undergoes one change before the activity vanishes or becomes too small for detection. The one active product is a solid one. In the case of radium, there was no difficulty in separating the successive products, for the emanation, being a gas, could be readily separated from the parent radium by heat; while the active deposit, being a solid, was readily separated in its turn from the parent emanation. Indeed, it may be said that the separation took place of itself. In the case of uranium, the separation of solid from solid is not quite so simple. Recourse must be had to the methods of chemical separation, of which we gained some knowledge in following the preparation of radium from pitchblende. We may employ the method of fractional crystallisation, which, though tedious, seldom fails of ultimate success. We may crystallise the uranium salts repeatedly, and determine whether the more soluble portions differed in their radio-active properties from those which were less soluble. This is the method which is used, as we saw, in separating radium from barium; and it was by this means that the active

product continuously produced by uranium was first separated. But there is another process which effects the desired separation much more easily. The uranium salt is completely precipitated in an insoluble form if we add to the solution of it a solution of ammonium carbonate. If we add more of this reagent, the precipitated uranium salt is redissolved. But a minute residue remains, which, though precipitated by the ammonium carbonate, in the first instance, is not, like uranium, redissolved by an excess of it. This residue is found to be intensely active photographically, but not markedly so when tested electrically. On the other hand, the uranium itself is about as active electrically as before, while its photographic activity has almost completely disappeared. The β-rays, it will be remembered, are responsible for practically all the photographic action, while the α-rays produce most of the electric leakage. So that the substance which has been separated emits only the β-rays, the uranium itself only α-rays. The new substance has been given the name of uranium X, or the unknown substance from uranium. Its β-radiation gradually decays, but this decay is much slower than any case of the kind that we have yet dealt with. For twenty-two days elapse before it sinks to one-half of its initial value.

In the meantime, the uranium salt, which had been freed from all uranium X, gradually acquires a fresh stock. The β-radiation begins to assert itself; and if the ammonium carbonate separation is carried out again, a fresh stock of the uranium X can be obtained.

The minute precipitate containing the uranium X by no means consists entirely of that substance. Its main constituent is iron, present as an impurity in

the uranium salt. The quantity of uranium *X* is so infinitesimal, that unless some impurity were present for it to collect upon, it would be impracticable to separate it. If no iron is present, it is necessary to add a little, in order to provide a nucleus for the trace of uranium *X* to gather on.

The case of thorium is complex. The first stage of transformation is into a solid, which by analogy with uranium *X* is called thorium *X*. In order to effect the separation, thorium nitrate solution is mixed with ammonia. The result is to precipitate the thorium in an insoluble form, as thorium hydroxide. The nitric acid, formerly in combination with the thorium, is now combined with ammonia as ammonium nitrate, and this, being a soluble salt, remains in the solution. If we filter off the solution from the precipitated thorium hydroxide, and evaporate it, the residue will consist chiefly of ammonium nitrate. This, however, like other ammonium salts, can be got rid of by heat, which decomposes it into volatile constituents. These are driven off, and a minute residue remains, which is found to be intensely radio-active, far more so than the original thorium salt. In some cases, the activity, weight for weight, will be found to be several hundred times as large. This residue consists mainly of thorium, which escaped precipitation by the ammonia. But its high activity is due to the new substance thorium *X*, which does not form an insoluble hydroxide, and is consequently not precipitated by ammonia.

Thorium *X* decays at about the same rate as the radium emanation, falling to one-half its quantity value in four days.

The method we have described is the only one by which thorium *X* has been satisfactorily separated from the parent thorium. It is not, of course,

asserted that it is the only possible method. The study of the chemical reactions of thorium *X*, as well as uranium *X*, is very important, and has not perhaps yet received all the attention it deserves.

It is found that the thorium *X* is responsible for about half the normal radio-activity of thorium. It is found, moreover, that the thorium which has been freed from it gives only α-rays.

The next change in this series is from a solid to a gas. Thorium *X*, in fact, gives off an emanation. This differs very remarkably from the emanation of radium, for it only lasts for a few minutes, while the radium emanation is still perceptible after a month. The time which elapses before the thorium emanation falls to one-half its initial value is rather under one minute.

In many respects the thorium emanation resembles that of radium. But the very short duration makes it more difficult to experiment with. The emanation can, however, be condensed by liquid air, and evaporates at a temperature only slightly different from the radium emanation. The thorium emanation, too, is chemically inert.

To obtain the thorium emanation, it is not, of course, necessary to obtain the thorium *X* first in a separated form. An ordinary thorium salt contains a stock of thorium *X*, which it has manufactured, and which it retains mixed with it. The salt will therefore give out emanation. Indeed the emanation from thorium salts was recognised long before the intermediate product, thorium *X*, had been realised. Many thorium salts give out the greater part of their emanation in the cold. The emanation cannot be extracted at a much greater rate by heating. In this respect thorium differs from radium. Some samples of thorium compounds are able to retain

all or nearly all their emanation in an occluded form. Others freely give up almost the whole of it. Thorium nitrate gives off very little of its emanation. Thorium oxide, on the other hand, gives up nearly all the amount generated. If, however, thorium oxide is heated to a white heat, it becomes able to retain its emanation after cooling. On dissolving up in acid and reprecipitating, the original properties are restored.

The thorium emanation, like that of radium, gives an active deposit which concentrates itself on a negatively electrified body. This active deposit, instead of being less durable than the emanation, is far more so. It appears to undergo two changes. The first modification gives out no rays, and decays to half the original amount in fifty-five minutes. The second does give off rays, and the corresponding time is eleven hours. The active deposit of thorium can be dissolved off the surface on which it has been formed, by means of acids. The acid, when evaporated in a dish, leaves the activity on the surface of the latter. Sulphuric or hydrochloric acid dissolves the deposit more freely than nitric acid.

Lastly, we have the case of actinium. This has been much less elaborately studied than the others, because the material is so very scarce, and has remained exclusively in the hands of very few.

Actinium gives off an emanation even less durable than that of thorium: for it only takes four seconds to fall to half its initial value. The emanation, as in the other cases, leaves an active deposit, falling to half value in forty minutes.

We may summarise the successive stages of degradation of the various radio-active elements so far as these have been traced in the following way.

Radium.—Solid—gas—solid—solid—solid—solid.

Uranium.—Solid—solid.

Thorium.—Solid—solid—gas—solid—solid.

Actinium.—Solid—gas—solid.

There seems to be no rule of sequence which holds good in every case. Nor are the various products produced in the order of durability. For example, the radium emanation gives a deposit less permanent than itself. The thorium and actinium emanations give one which is far more permanent.

With regard to polonium, it appears that the activity decays, falling to half value in about a year. But no experiments have been published, so far as the author is aware, which give information as to the products of its decay.

All chemical changes are accompanied by thermal effects. When oxygen combines with hydrogen, heat is given out, or, to take a still more familiar case, when carbon combines with oxygen, as in the combustion of coal. There are instances in which the product is more complex than the original constituents. But heat is often evolved in the decomposition of a complex substance. The most conspicuous examples are the explosive compounds which have taken the place of gunpowder in modern blasting operations. Nitro-glycerine, which is the active principle of dynamite, gives off a large amount of heat in its decomposition. It has been found that the changes taking place in radium also give rise to thermal effects. One of the original experiments on this subject by MM. Curie and Laborde, to whom we owe the discovery, was made by means of Bunsen's ice calorimeter (fig. 24) an instrument admirably adapted to the measurement of small quantities of heat.

The working of the instrument depends on the fact that water expands on freezing. This effect is

familiar to all in the bursting of frozen water-pipes. It is an obvious consequence that ice must contract on melting. If, then, we can measure the contraction, it will be evident that the amount of ice which has been melted is quite determinate. The quantity of ice

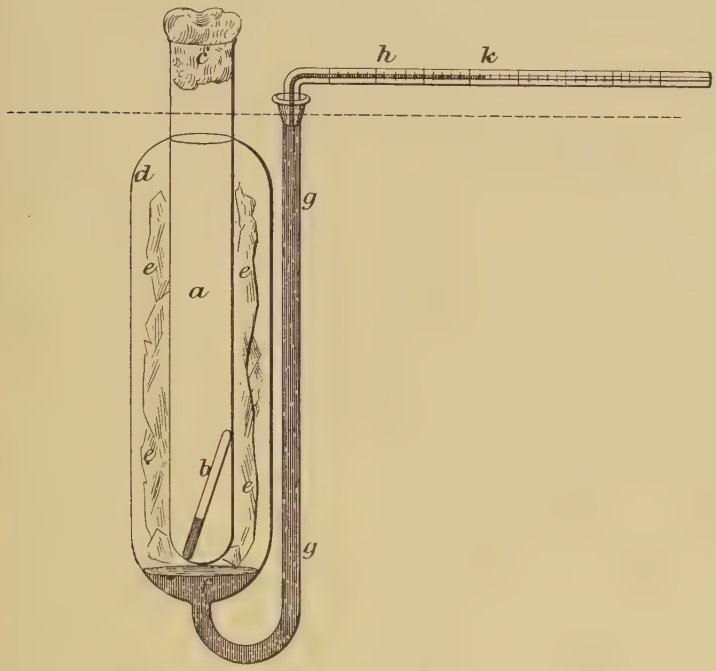


FIG. 24.—Bunsen's ice calorimeter, used in observing the heating effect of radium. *a* is a vessel like a test tube, into which the sealed tube, *b*, containing the radium, can be dropped. *a* is plugged at *c* with cotton wool, to guard against external heating. Round *a* is the outer chamber, *d*, which is quite full of freezing water, with a lump of ice, *e e e e*, round *a*. The bottom contains mercury, as does also the side tube, *g g*, and the horizontal graduated tube, *h*, of small diameter. The whole instrument is packed in ice up to the level of the dotted line, to prevent heat getting in from outside. While the radium is inside, the end, *k*, of the mercury thread is observed to be constantly receding, owing to the melting and contraction of the ice by the heat it liberates. As soon as the radium is withdrawn the thread becomes again stationary.

melted serves to measure the amount of heat which has been employed in melting it; for standard experiments have been made on the amount of heat required to melt, say, a pound of ice.

To carry this method into practice, a double-walled vessel is used, as shown in the figure. The space

between the walls is entirely filled with water, a part of which is frozen. Below the water is mercury. This mercury extends to the narrow graduated tube, in which it forms a thread, as in a thermometer. The position of the end of the thread can be read on the scale, just as in reading a thermometer.

To prevent the ice between the walls of the vessel getting melted by the heat of the room, the whole instrument is packed in ice. The narrow graduated tube, and the mouth of the vessel, alone project.

If now a little radium is introduced inside the vessel, it is found that the end of the mercury thread begins to recede. The contents of the vessel are contracting, or, in other words, the ice between the walls is melting; and this goes on indefinitely. As soon as the radium is withdrawn, the end of the mercury thread remains steady. When the radium is again introduced, the mercury thread begins to recede steadily, and continues to do so, so long as the radium is left inside.

We saw above (see p. 32) that it had been suggested that radio-active bodies drew their supplies of energy from the surrounding air. If this were so, the molecules of the surrounding air would lose energy, and its temperature would fall. The experiment we have just described conclusively proves that this is not the case. For, if the heat emitted by the radium were drawn from the surrounding air, there should be no heating effect on the whole from the air and the radium taken together. But the air was included with the radium inside the calorimeter, and the heating effect is observed none the less. It is evident, therefore, that radium does not draw its energy from this source.

Let us return now to consider more quantitatively the experiment with Bunsen's calorimeter.

If we know the size of the graduated tube, and if we found the rate at which the mercury moves, it is easy to find the change of volume in an hour, and to calculate the amount of ice which has been melted in that time. The result is to show that radium can melt something like its own weight of ice in an hour. The amount of heat required to do this is not very different from what is required to raise the same quantity of water to the boiling point, starting at the ordinary temperature. So that we may say, if we prefer, that radium gives off enough heat in an hour to boil its own weight of water.

A pound of radium, if we could obtain so much, would be capable of boiling a pint of water in an hour. It would give off as much heat as a small spirit lamp.

If we reflect that radium probably retains its powers quite undiminished for hundreds if not thousands of years, it will be admitted that this is one of the most astonishing results in the whole range of science.

The quantities of radium available to experiment with are, as we have seen so often, very small; so that they expose, in proportion to the amount of heat liberated, a very large surface. This enables the heat to get away easily. No part of a small mass of radium is very far from the surface. And thus it happens that the temperature does not rise very high. In spite of this, M. Curie has been able to show the heating effect of a fraction of a gramme of radium, by means of an ordinary mercury thermometer, which was heated several degrees hotter than the surroundings.

If a large mass of radium could be obtained, say a few pounds, the inside would probably be vividly incandescent, with the heat generated. For the outside layers would serve to hinder the escape of the

heat generated by the internal portions. Thus the temperature would be able to rise very high.

A most mistaken notion has got abroad that the heating property of radium may have a direct practical application. A little consideration will show the utter futility of such an idea. Radium can give off enough heat to melt its own weight of ice in an hour. Coal can give off enough heat in the process of complete combustion to melt about 100 times its own weight of ice. Perhaps this process of complete combustion may take some five hours, in the case of a domestic fire. Thus the burning coal gives off heat at twenty times the rate that the same amount of radium will do. The radium-filled grate would require to be twenty times larger than the coal one to produce the same effect. True, the radium would practically not require replenishing. But if we reflect that an ounce of radium costs £30,000, it will be admitted that a good deal more heat might be obtained by investing the money in consols, and devoting the annual interest to the purchase of coal!

The heating effect of radium even when so sparsely distributed as it is in pitchblende, would probably be perceptible inside a large block. A rough calculation, on certain reasonable assumptions as to the rate at which heat was conducted through the substance, showed that, in the middle of a large slab a yard thick, the temperature would be something like one-fifth of a degree. It is not impossible that inside a deep mine, where pitchblende was very abundant, the temperature might be perceptibly higher from this cause.

For a long time the source of the sun's heat was regarded as very mysterious. We know, with fair accuracy, the size of the sun, and the density of the

material of which it is constituted. On any reasonable view of the amount of heat which such a body could give out in cooling, it seemed very difficult to understand what could be the source of the enormous quantities of heat which the sun pours out in all directions. For we know with tolerable accuracy the amount of heat which reaches a square yard of the earth's surface, from the sun, every hour. And assuming, as we safely may, that an equal amount of heat is given out by the sun in every other direction, the amount of heat given out altogether may be computed.

When this is done, it is found that if the sun had no resource but to draw on its own primeval heat, it could not go on very long without becoming perceptibly colder.

As this does not happen, we must suppose that the sun has some other source than its primeval supply to draw upon.

The most natural source to look to is perhaps combustion. But here again, if the sun was made of the most combustible materials known, this source of supply would not last nearly long enough.

The view which, until lately, has exclusively held the field is that propounded by Von Helmholtz. His theory assumes that the sun is contracting; that its diameter becomes less every year. In short, that the outer parts are falling down on the inner ones.

Whenever one body falls on another, heat is developed. For instance, iron may be made visibly red hot by skilful and vigorous hammering. The method was employed by blacksmiths as a means of kindling a fire before the invention of matches.

It is just in this way that the heat of the sun is assumed to be maintained by contraction, and consequent falling in of the outer parts on the inner ones.

It might be thought that this cause would be inadequate to explain the origin of sun's heat. But calculation shows that it is adequate. For a rate of contraction altogether imperceptible by the most refined measurements of the sun which we can make, would suffice to maintain the output of energy.

The discovery of the wonderful supplies of energy which radium possesses, and can give out, suggests another possible explanation of the origin of the sun's heat. It has been estimated that if the sun contained two and a half parts of radium in a million, by weight, the present output of solar energy would be accounted for. If, in fact, the sun were only a little richer in radium than the best pitchblende, we should not have to look any further for the source of its heat.

A circumstance strongly confirmatory of the idea that a part at least of the sun's energy is derived from radium is the abundance of helium in the solar atmosphere. For we shall see in a later chapter that helium is a product of the changes occurring in radium. If the sun is really rich in radium it should be radio-active. No radio-active effect due to the sun has, however, yet been traced. An electroscope will retain its charge just as long when exposed to the sunlight[1] as when taken into a tunnel with many feet of rock overhead. This has been regarded as a formidable objection to this theory of the sun's heat, but it is not really so.

We must remember, in the first place, that the radium is supposed to be disseminated uniformly throughout the sun's volume. Now the Becquerel rays cannot penetrate any great distance through solid materials; so that the rays from the internal

[1] It is necessary to take precautions to exclude what are called photo-electric effects, which have nothing to do with radio-activity.

portions cannot escape. The radium contained in a very thin outer shell could alone produce any external electrical effect.

If we reflect further, that the earth's atmosphere produces an absorbent effect equivalent to a column of water 32 feet high, it will not be difficult to understand that the Becquerel rays from the sun cannot easily get through. As a matter of fact, calculation shows that the amount of effect to be expected, assuming that the sun's heat is wholly due to radium uniformly distributed throughout it, would be utterly beyond the range of experimental detection.

Professor Rutherford and Mr. Barnes have carried the investigation of the heating effect in radium a stage further than did the original discoverers of the effect; for they have investigated the amount of heat liberated in the formation of each of the successive radio-active products.

They measured the heating effect from a specimen of radium bromide. They then heated the salt and removed the emanation, which was collected in a small glass tube and sealed up.

It was found that the heating effect of the radium salt was diminished by the loss of its emanation in exactly the same ratio as the radio-activity was diminished, that is, if the α-rays alone are taken into account. On the other hand, the heating power which had been lost by the solid was found to survive unaltered in the gaseous emanation. The heating power of the two added together was exactly the same as if no separation had been effected.

It was found that the tube containing the emanation lost its heating effect in just the same way as the emanation loses its activity. For the heating effect fell to half its initial strength in 3·7 days,

just as the activity of the emanation falls to half value in that time.

The radium deprived of emanation recovers its heating power just as it recovers its activity.

In fact, it was found that the heating effect of a radio-active product was at all times proportional to the amount of α-radiation it was emitting. This applies equally to radium itself, to the emanation, and to the active deposit.

The discovery of the enormous quantities of energy liberated by radium is a proof that there lies latent in the atom a quantity of energy absolutely gigantic in comparison with anything which it was formerly believed to contain.

Energy is often liberated, as we have seen, when chemical combination takes place. The most conspicuous case is the combination of oxygen and hydrogen to form water, for more heat is given out in this case than in any other that has been investigated. The energy liberated in the formation of a pound of water would be supplied by a pound of radium in forty hours. We do not yet know with certainty how long radium will last, how long, in fact, it will continue to evolve heat at this rate, but there can be no doubt that the period is to be measured by hundreds or thousands of years. So that the amount of energy which the pound of radium possesses must be millions of times greater than energy which is set free in any known chemical change in an equal quantity of material.

It was formerly thought that the energy liberated in chemical changes was a considerable fraction of what was present altogether, although, of course, it was recognised that there was no proof of this. But this view must now be altogether abandoned, for the case of radium can hardly be regarded as exceptional.

It is true that this is the only case where measurable quantities of energy are being given off.[1] But it is the giving off of the energy which we must alone regard as exceptional. It must be assumed to be present, in a latent form, in other chemical atoms also.

It is not inconceivable that some process might be discovered which would enable us to liberate such stores of energy on a large scale in the case of ordinary materials—to make large quantities of them radio-active. If this could be achieved, the problem of the failure of the coal supply need never cause any further anxiety.

We may conclude this chapter by saying something about the effect of temperature on radio-active processes.

M. Becquerel has experimented on metallic uranium to see whether heating it or cooling it would alter the radio-activity. As he has remarked, metallic uranium has been subjected to a tremendous heat in the electric furnace during the process of manufacture. It is evident, therefore, that intense heating cannot permanently destroy radio-activity. It remained to investigate the question of whether a temporary effect was produced while the uranium was still being heated or cooled.

Experiments of this kind are difficult because heating or cooling the air may, and in fact certainly does, affect the discharging power, apart from any change in the activity of the radiating substance. For this reason it is easiest to work with the β- or γ-rays, which can be detected at a distance from the uranium. The temperature of the uranium can then be varied without altering the temperature of the air in which the electric leakage is to be measured.

[1] Uranium and thorium no doubt produce similar though much smaller effects. But no attempt has been made, so far as I know, to detect these.

When this arrangement was adopted it was found that the activity of the uranium was quite unaffected by changing its temperature. The discharging power was just the same, whether the uranium was heated to the temperature of boiling water, or cooled to the temperature of liquid air.

With radium it is otherwise. Heating diminishes the apparent activity. This, however, is not due to any real change of activity, but to loss of the emanation, which contributes largely to the activity of radium as ordinarily observed. If the specimen is sealed up in a glass tube, so that the emanation cannot escape, no change of activity is observed.

Not only is the Becquerel radiation unaffected by temperature; the rate at which heat is liberated is unaffected also. Just as much heat is given off by radium maintained at a low temperature as at the ordinary temperature. This has been shown by some experiments of M. Curie, carried out in conjunction with Professor Dewar. The method adopted differed from those by which the earlier experiments were made. It depended on the evaporation of a liquefied gas.

To take a specific case, let us consider the evaporation of liquid hydrogen. This liquid when boiling is only some twenty degrees above the absolute zero of temperature. Any heat which obtains access to this liquid at its boiling point instantly causes actual ebullition. Now, no matter what precautions may be taken in the way of screening off external heat by vacuum jackets or wool wrappings, some is certain to find its way in and cause the liquid hydrogen to boil. This boiling would interfere with the experiments; in order to avoid it the liquid hydrogen vessel was immersed in a larger vessel, also containing liquid hydrogen (fig. 25). Slight ebullition in the outer

vessel was unimportant; since, however, the temperature of the outer vessel could not rise above the boiling point of liquid hydrogen, the access of heat to the inner vessel was prevented, and the liquid in it was perfectly quiescent.

As soon as a sealed tube containing radium was introduced, the hydrogen in the inner vessel began to boil off. That would occur with any substance, since

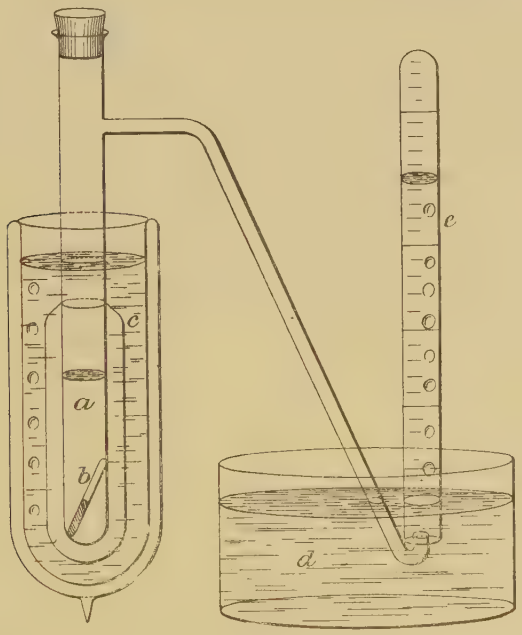


FIG. 25.—Measurement of the heat emission of radium at the temperature of liquid air or liquid hydrogen. A double-walled vessel, *a* (vacuum jacketed) contains the liquid hydrogen. The radium, *b*, in a sealed tube, is immersed in this, and causes ebullition. The evolved gas is collected over water in *d*, in a graduated tube, *e*. To prevent the access of external heat, *a* is immersed in an outer vessel, *c*, also containing liquid hydrogen.

some ebullition may occur in the process of cooling it down to the low temperature. After that no further boiling would occur in ordinary cases. With radium, however, the boiling went on quite steadily and uniformly, as long as there remained any liquid hydrogen in the vessel. This is due to the heat

steadily given off by radium, which we have discussed.

The volume of gaseous hydrogen liberated by the boiling evidently gives a measure of the quantity of heat liberated. The evolved hydrogen was measured by collecting it in the ordinary way over a pneumatic trough, in a graduated tube. It is, of course, necessary to know how much heat is liberated in boiling off, say, one litre of hydrogen. This, however, has been determined by standard experiments. The first determinations seemed to show that even more heat was liberated at the temperature of liquid hydrogen than at the ordinary temperature. More accurate experiments, made later, led to the conclusion that the rate of evolution of heat was quite unaffected by cooling in liquid hydrogen.

The contrast, in this respect, between the changes going on in radium, and ordinary chemical change, is very striking. There is only one chemical reaction —the combination of hydrogen with fluorine—which is not arrested by cooling to this extent. The enormous majority of chemical changes are altogether stopped by cooling to the temperature of liquid air, which is, on the absolute scale, some four times hotter than liquid hydrogen; almost all of them are profoundly affected by changes of temperature. The changes occurring in radium are not influenced in the least by heating or cooling.

CHAPTER VI

RADIO-ACTIVITY IN THE EARTH AND IN THE ATMOSPHERE

It was mentioned in Chapter II. that some soils contained radium. We shall now describe some of the experiments by which this has been proved to be the case. In the first place, it is found that the air in cellars or caves possesses a marked ionisation.[1] This has been traced to the presence of radium in the soil; the emanation of this radium diffuses into the air of the cave or cellar from the surrounding soil, and ionises it. The same effect can be obtained still more conspicuously by sinking a pipe into the earth, say a yard down, and sucking up a sample of air from the soil. Such air possesses marked conductivity; the conducting power falls to half its initial value in a little less than four days. This shows that it is due to the radium emanation.

No very complete investigation of the amount of radium in various soils has yet been made. Clay soils are usually the most active, but Professor J. J. Thomson has found the sand from the beach at Whitby to be very active too.

Much more active than any ordinary soil is the deposit left by the water of certain thermal springs. The author has found strong emanating power in the deposits of Bath and Buxton. The water of these

[1] This ionisation is much larger than that observable in closed vessels, which will be discussed later.

springs rises from great depths below the earth, and reaches the surface very hot. At Bath the temperature of the water at the spring is higher than can easily be borne. As the water cools it deposits a fine red mud in the tanks and pipes. This mud is found to give off radium emanation in abundance, though not, of course, nearly so strongly as pitchblende. The mud deposited near the spring is stronger in emanating power than what is deposited further away.

As the mud separates from the water, there is necessarily some radium in solution in the water. The quantity, however, is exceedingly small; nor is this surprising, for the water contains abundance of sulphates in solution. These would precipitate any radium that might be present in the form of insoluble radium sulphates. Radium sulphate is one of the most insoluble salts known, so that the quantity of radium remaining unprecipitated is necessarily very slight indeed. Whether the water is saturated with radium sulphate has not yet been decided.

The author has estimated the quantity of radium annually delivered by the spring as about $\frac{1}{3}$ of a gramme. This, if isolated, would be a quantity not to be despised; but to separate it economically from the vast mass of water and saline material with which it is associated would be quite impracticable.

It is interesting to note that the Bath spring yields helium as well as radium. If the surface of the water over the well of the King's Bath be watched, bubbles of gas will be seen to constantly rise to the surface and break there. The gas has been examined from time to time by various chemists. The earlier investigators reported that it was mainly nitrogen. After the discovery of argon it was realised that the purely negative tests, before considered sufficient to identify a gas as nitrogen, were insufficient; for

they did not distinguish it from the other inert gases, helium, neon, argon, krypton, and xenon.

In the light of this discovery Lord Rayleigh re-examined the Bath gas, with the idea that it might prove to be mainly argon. This hope was disappointed; for the gas was found to mainly consist, as had previously been supposed, of nitrogen. The percentage of argon in it was not very different from the percentage of argon in the atmosphere; but the interesting observation was made that the gas contained about one part of helium in a thousand, by volume.[1]

The presence of helium, it cannot be doubted, is connected with the presence of radium.[2] In all probability the Bath spring draws its supplies of both materials from the disintegration of radio-active minerals.

Many samples of ordinary well waters which have percolated through the soil are found to contain radium emanation in solution. The emanation is fairly soluble in water, considerably more so than oxygen or nitrogen, though less than carbonic acid. Thus the dissolved gases boiled out from the water are often quite markedly radio-active. The emanation has been no doubt dissolved by the water in percolating through strata which contain traces of radium.

The first case of this was noted by Professor J. J. Thomson, who found that the Cambridge tap-water would yield, on boiling, a gas containing the emanation. When once the emanation has been boiled out, no more, or at all events very little, can be got on

[1] Professor Dewar has subsequently utilised the helium of the Bath spring in his attempts to liquefy that gas. He has found that this helium contains some six per cent. of neon. This points to a far larger proportion of neon in the Bath gas than in the atmosphere.

[2] See below, chap. VII.

a subsequent occasion. Thus the radium salt from which the emanation was derived is not present in the water.

In the case of the Bath springs, the water contains far more emanation in solution than corresponds to the dissolved radium. The gas bubbling up to the surface also contains emanation. This suggests that the water has had access to large quantities of radio-active minerals, and that it has only disintegrated a small portion of them.

Elster and Geitel were the first to discover that the atmosphere contains radio-active matter. Their experiment was as follows. A long negatively electrified wire was hung up in the open air, and after exposing it for some hours, it was coiled up to manageable dimensions and tested for radio-activity with the electroscope. The result was to show that the wire had become active. No effect of this kind is observed when the wire is positively charged.

Now it will be remembered that a negatively charged wire when immersed in the emanation of thorium or radium, is able to collect the active deposit formed by the degeneration of the emanation. Thus it is fair to conclude that the active deposit collected by a negatively charged wire in the open is due to the presence of a radio-active emanation in the atmosphere.

The rate of decay of the active deposit from the air has been carefully investigated. The activity does not fall off according to the simple law of compound-interest, but behaves irregularly, like the active deposit of radium. It is, of course, more difficult to compare two irregular decay curves than two regular ones, since the shape of the curve depends on the time of exposure; but, upon the whole, it appears fairly certain that the active deposit obtained

in the open may be identified with that of radium; and it would follow that the atmosphere contains radium emanation.

There is another and simpler way, in which the active deposit of the atmosphere may be collected. Mr. C. T. R. Wilson observed that freshly fallen rain, quickly evaporated to dryness, left a radio-active deposit on the basin in which it had been boiled down. The same effect is obtained from snow or hail. The active deposit thus collected dies away in the same way as that collected by a negatively charged wire, and is almost certainly identical with it.

The amount of activity to be collected from the atmosphere varies very much according to locality and circumstances. Elster and Geitel carried out a systematic series of measurements lasting over a whole year. The largest activity they obtained was no less than sixteen times the smallest. These experiments were made at Wolfenbuttel, in the middle of Germany. Mr. Simpson has recently made experiments in the extreme north of Norway, with the interesting result that the activity there is seldom less than the very highest ever found at Wolfenbuttel, and on one occasion seven times as large. During these experiments the ground was covered with deep snow.

It has been found that wind is favourable to large radio-activity. This is not surprising, since larger quantities of air come within the range of action of the charged wire when a wind is blowing than when the air is still.

The most probable source of atmospheric radio-activity is radium emanation, which has diffused out from the soil, and thus found its way into the air. If this is the true explanation, we should expect less activity on the sea-coast than inland; this anticipa-

tion has been found to agree with experiment. But it would be rash to infer too much from this until more extensive measurements have been made, especially in mid-ocean. On this view, the activity of the air will depend on the quantity of radium in the soil; the high values obtained by Mr. Simpson would be due to the comparative richness of the surrounding strata in radium.

When the barometer falls, and the pressure of the air becomes lower, the air imprisoned in the pores of the soil will be to some extent forced out into the atmosphere above. Thus high radio-activity in the atmosphere should accompany a low barometer. Elster and Geitel have found that this usually is the case. Sometimes, however, the radio-activity quickly increases when the barometer is rising. The explanation of this is obscure. But it must be remembered that wind and other causes probably intervene. The whole subject affords an interesting field for investigation.

RADIO-ACTIVITY OF ORDINARY SUBSTANCES

A gold-leaf electroscope, well insulated, and placed in an exhausted vessel, will retain its charge for very long periods. Sir William Crookes, many years ago, made an experiment on this subject. He hung up a pair of gold leaves in an exhausted glass bulb, and found that they remained divergent for months. It is found, however, that if air be admitted to the vessel, the leaves do not retain their charge for more than a moderate number of hours—perhaps twenty-four or thirty-six hours.

For a long time this was regarded as due to a failure of the insulation, owing to the admission of dust or moisture with the air. But the subject did

not attract much attention, and its importance does not seem to have been realised.

Some of those who knew the facts—and they were few—seem to have considered that the escape of electricity was due to a brush or spark discharge through the air, by which the electricity escaped from the leaves. But there is a fatal objection to such a view; for a brush discharge cannot occur in air unless the electric stress amounts to something like thirty thousand volts per centimetre. In the experiments we have mentioned it is more like one hundred volts per centimetre; so that this explanation is untenable.

Light was first thrown on the subject in some experiments by Mr. C. T. R. Wilson. He found that the current which leaked away from the leaves became saturated—that is, that it was independent of the electro-motive force if the latter was large enough. Further, he found that the relative ionisation in different gases was the same as the author had found for the same gases when strongly ionised by the Becquerel rays. Taking these facts together, it seemed probable that the discharge through ordinary air was intimately connected in some way with radio-activity.

The next step was made at about the same time by several experimenters. It was shown that the rate at which the charge was lost depended on the nature of the walls of the vessel. For instance, in some experiments by the author it was found that when the walls were lined with platinum, the rate of discharge was three times as great as with zinc. It was found, moreover, that the rate of discharge, though quite definite with a given sample of platinum, was different when another sample was employed. The most natural interpretation of this result would be

that the activity was due, in part at least, to the presence of a trace of some intensely active substance such as radium in the platinum. This would explain quite satisfactorily the want of constancy; for some samples would be sure to contain more of the impurity than others. In any case, it appears certain that the loss of charge in ordinary air, which had been known for so many years before the recognition of radio-activity, was, in reality, an example of it. It is rarely, indeed, that a discovery is so new that nothing bearing upon it is to be found in scientific literature.

The activity of these ordinary materials is exceedingly minute. Thus the author estimated the activity of a sample of platinum more active than most substances at $\frac{1}{5000}$ of the activity of uranium. So that radium would be no less than three thousand million times more active than this piece of platinum. A very interesting discovery was made at about the same time by Professor Maclennan and Mr. Burton at Toronto, and Mr. H. L. Cooke at Montreal. It was found that the rate of discharge of an enclosed electroscope containing air could be diminished by building a thick screen of lead round it, or by immersing it in a tank of water. The diminution which could thus be produced was about one-third of the whole conductivity.

It seems, then, that there must exist everywhere extremely penetrating rays, which are able to get through ordinary thicknesses of metal, and which can produce ionisation in gases, but which can be stopped by great thicknesses of metal or water. These rays are, so far at least, of the same nature as the γ-rays of radium, and their penetrating power seems to be about the same.

Mr. Cooke made some experiments to find out

what direction these rays came from, whether from the earth, from the sky, or from a horizontal direction. He placed a thick metal screen, first over the top of the electroscope, then at the side, then underneath, and came to the surprising conclusion that the rays proceeded equally from all these directions. This was equally the case in the open air as in buildings.

It has been mentioned in an earlier chapter that some kinds of soil contain traces of radium. It will be understood, therefore, that γ-rays may be expected to pass upwards from the earth, especially in localities where the soil is active. We know, too, that the atmosphere usually contains radium emanation; there is, therefore, nothing surprising in γ-rays coming from above, and sideways. But it is very difficult to see why the amount of radiation from above should be the same as the amount from below. The strength of the radiation must depend on the percentage of radium present, and on the absorption by the material of the air; and it would seem to be an extraordinary coincidence that these should be so proportional as to give the same radiation from above as from below. Moreover, the amount of emanation in the air varies from day to day. So that even if the radiations were equal on one occasion, it would seem inexplicable that they should always be so.

For these and other reasons, Professor J. J. Thomson is of opinion that the γ-rays of radium are not the rays principally concerned in these experiments, but that some new kind of penetrating radiation is given out by all substances in proportion to their densities. It seems, however, in some ways undesirable to postulate an entirely new cause for the effect, until it has been more thoroughly

proved that the old one cannot be made to account for it.

Mr. Campbell has recently given a preliminary account of some experiments which have led him to conclude that, in the case of some metals, the apparent radio-activity of the walls of the vessel is due in part to a kind of secondary radiation set up by the penetrating radiation from outside. This is analogous to the behaviour of heavy metals when transmitting the Rontgen rays; they are known to give off a secondary radiation, much less penetrating than the primary.

It will be seen from this brief sketch that the subject of the apparent radio-activity of ordinary materials is a subject of great complexity. No doubt in a short time it will be possible to give a far more satisfactory account of it than at present.

CHAPTER VII

THE ULTIMATE PRODUCTS OF RADIO-ACTIVE CHANGE

We have followed in chapter v. the changes occurring in radium, and the other radio-active elements, so far as these are known. It must be observed, however, that in all probability many more changes occur than are yet recognised. In the case of radium we have the apparently permanent residue (amounting to $\frac{1}{20000}$ of the whole) from the active deposit. It is true that this activity is slight. But then it is very durable. Professor Rutherford considers it probable that the same total amount of radiation is given out at every stage of decay. Thus, the emanation gives out as much radiation, weight for weight, as the parent radium, and so on for the other changes. This cannot hold universally, because some of the products do not give out rays at all, and one at least, uranium *X*, gives only β-rays. But it often seems to hold good. Thus, the slightly active permanent residue may be just as important a step as the others. We have spoken of it as permanent, but in all probability prolonged observation will show that it does decay, though very slowly.

The activity of uranium *X*, and of the thorium deposit, very possibly do not vanish, but have a small residue, not yet detected.

In course of time, however, the activity must disappear; for the quantity of energy originally present

was limited, and cannot keep up Becquerel radiation, with attendant liberation of heat, for ever. We are face to face, then, with the question, What becomes of these products when they have lost all radio-activity—when, in fact, they have ceased changing, and have settled down to a permanent condition?

We have seen how exceedingly minute are the quantities involved. While the radio-activity lasts, that scarceness does not altogether bar the investigation of their properties. For it is possible to ascertain the presence of the various products, and to measure their relative amount, by observations on their radio-activity. In fact, such observations answer, in large measure, the same purpose as would be attained by seeing and weighing the substances.

When, however, the radio-activity has gone, we can no longer employ this method. And the difficulty of pursuing the investigation further becomes very great. In the first place, it will be remembered that radium was found in certain minerals. Now, if radium is degenerating by successive stages into some other substance, is it not reasonable to assume that, in the course of countless ages, the radium in such minerals will have generated a fair amount of such products? If this be granted, we must consider what other substance is present in all the minerals which contain radium.

Now these minerals are of extraordinary complexity. There is hardly any element that is *not* found in them in greater or less quantity. So that the clue is a very poor one.

There is one substance in particular, however, which is present very persistently in the radio-active minerals, and which in some ways seemed to be a likely product of radio-active change. That is the element helium.

It will be desirable to digress somewhat from our subject, to give an account of this gas, and the history of its discovery.

Lord Rayleigh had for many years been determining the density of gases, with a view to attaining the highest possible precision. All previous experimenters who had determined the density of nitrogen, the inert constituent of the atmosphere, had contented themselves with removing the other known constituents of the air, and weighing the inert residue as pure nitrogen. Lord Rayleigh, however, considered it desirable, as a measure of precaution, to determine the density of nitrogen from other sources, such as ammonia, or nitric acid, in addition. He found, to his surprise, that these chemically prepared samples of nitrogen were all consistently lighter by about one part in three hundred than the nitrogen of the air. This was a very surprising result. For no one doubted, at that time, that the nitrogen of the air, and the nitrogen of saltpetre, or, what is the same thing, of nitric acid, were identical. The general tendency was to attribute the discrepancy (which after all was not large) to some oversight. But further experimenting entirely confirmed its reality. And, in the end, it was found (by Lord Rayleigh and Sir William Ramsay, working in collaboration) to be due to the presence of a hitherto unsuspected constituent of the atmosphere, of about one and a half times the density of nitrogen, present to the extent of about one per cent. In order to obtain it, it was necessary to absorb the nitrogen in which it existed.

Nitrogen is very inert. It was, and in some degree still is, a matter of great difficulty to induce it to enter into chemical combination. One of the methods adopted for absorbing it, was to submit the gas to

the action of red-hot magnesium. The absorption is very slow. But in the end all the nitrogen taken was induced to combine with magnesium, and a residue was found to remain over, which refused to combine. This inert residue was termed argon, and it was found to be absolutely indifferent to every chemical re-agent, however active. It appeared, in short, to be incapable of entering into combination with any other substance. We have seen that in this respect it resembles the emanations of radium and thorium.

After the discovery of argon, it became clear that caution was necessary before any inert gas which might be encountered in nature could be accepted as nitrogen. It had been usual, in analysing gases, to test for the oxygen and for hydrogen carbonic oxide and combustible gases generally. The inert residue was entered, without further examination, as nitrogen. It was for this reason that argon had remained so long undetected. But, at last, it had been realised that the inert residue must be more minutely examined before its nature could be stated. Now it was known that certain minerals, notably cleveite, a variety of pitchblende, gave off an inert gas on heating. This gas, as usual, had been regarded as nitrogen. In the light of the discovery of argon, Sir William Ramsay thought it worth while to look into the nature of the cleveite gas more closely. He found that it was not nitrogen or argon, but another new gas, distinct from either.

Many years before, Sir Norman Lockyer had observed in the spectrum of the sun's chromosphere a strong line in the yellow near the lines due to sodium. He had not been able to identify this line as due to any known terrestrial substance, and had concluded that it was not due to any such substance, but to an

element present only in the sun. He accordingly named it helium. The characteristic helium line was afterwards observed, not only in the sun, but also in many of the stars.

When the light emitted by the cleveite gas under the influence of the electric discharge was examined, it was found to give the characteristic yellow line of helium. Terrestrial helium had at last been found.

Helium is quite inert chemically, like argon. It cannot be made to enter into combination with any known substance, nor can it be induced to recombine with the original mineral when it has once been driven off by heat.

Helium is a very light gas; its atom is only four times as heavy as that of hydrogen. It is even more volatile than hydrogen, and enjoys the distinction of being the only gas which has yet resisted liquefaction by cold and pressure. If its liquefaction should ever be achieved, we shall be able, by using the liquid, to produce a lower temperature than in any other way. The anticipation is that a temperature removed by only five degrees (centigrade) from the absolute zero would be attainable.

The suggestion that helium might be found to be an ultimate product of radio-active change was first made by Professor Rutherford and Mr. Soddy. The honour of showing that radium did as an undoubted fact produce helium is due to Sir William Ramsay and Mr. Soddy. The observation is one of great difficulty, and nothing but the highest experimental skill could have brought it to a successful issue; for the quantity of radium available to experiment with is necessarily small, and the yield of helium almost inconceivably minute.

In order to recognise the presence of helium it is

necessary, as we have said, to pass an electric discharge through the gas, and to examine the luminosity which results by means of the spectroscope. The luminosity of the gas under the electric discharge is greatest when at a low pressure, perhaps one-hundredth part of the atmospheric pressure. This circumstance is favourable when, as in the present case, the quantity available for experiment is almost infinitesimal.

In examining the spectrum of a gas at a low pressure under the influence of the electric discharge, the form of tube devised by Plücker is commonly employed.[1] Sir William Ramsay and Mr. Soddy constructed a tube of this kind of the smallest possible volume, so as to economise gas to the uttermost. They exhausted this with the mercury pump, so as to get rid of all traces of air. They then introduced the pure accumulated emanation of fifty milligrammes of radium bromide.

It will be understood that to extract and manipulate quantities of gas of the size of a pin's head is no easy matter. Sir William Ramsay, however, has had unrivalled experience in this kind of work; for it is to him and to Dr. Towers that we owe our knowledge of the rare gases neon, krypton, and xenon present in minute traces in the argon of the atmosphere. In dealing with the very small quantities of these gases which are procurable, methods of gas manipulation were devised which enabled such small quantities to be dealt with quite satisfactorily. It was by a further refinement of these methods, which are of too technical a character to be described here, that the pure emanation was successfully transferred to a small Plücker tube.

The spectrum of this gas was observed immediately.

[1] Chapter I., page 2.

It appeared to be different from any known spectrum.[1] After a few days, however, this unknown spectrum was found to have faded away, and the helium spectrum had asserted itself in its place. The yellow line known as D_3, first observed by Sir Norman Lockyer in the sun, and subsequently observed in terrestrial helium, could be distinctly observed. In short, the emanation had turned, partially at least, into helium.

It would scarcely be too much to say that this is one of the most important experimental results ever attained in chemical science; for it is the first recorded instance of a transmutation of the elements. There are some seventy elements known. Of these a few, principally the common metals, such as iron, copper, tin, lead, gold, were known to the ancients. The large majority, however, have been left to modern science to discover. Up till recently all attempts to produce any one of these substances from another had failed. The alchemist's dream of transmuting silver into gold is familiar to all, though why silver should be a specially more promising material to produce gold from than any other is not, from the chemist's point of view, very apparent.[2] It may have had its origin in some vague notion that as silver and gold were both 'noble' metals, there might not be much difference in their nature. In spite of the entire failure of any chemical process of solution, distillation, or precipitation to effect the smallest transmutation of the elements, it was felt that there

[1] Sir William Ramsay and Professor Collie have recently made a detailed study of the spectrum of the emanation. It can only be observed with difficulty; when obtained it resembles those of the inert gases, argon and its companions.

[2] This was a sufficient reason for feeling great scepticism about the alleged success of an American attempt to produce gold, which achieved some notoriety a few years ago. The process was to hammer silver at a very low temperature.

must be some solution to the riddle of their separate existence, and that that solution was not wholly beyond what science might hope to reach; for there were hints of a connection between the elements—hints, in fact, that they all formed part of one scheme.

It was noticed that when the weight of the other atoms was expressed in terms of the weight of the hydrogen atom, the lightest of all, they approached, in many instances, very closely to whole numbers. The other atoms were very nearly an exact number of times as heavy as the hydrogen atom. It was not at first unnatural to assume that an exact law of nature was in question, and that the departure of the atomic weights from whole numbers was due to the unavoidable errors of experiment.

Such a theory was very attractive, for it would almost irresistibly lead to the conclusion that the other atoms were built up of a number of hydrogen atoms. At the time the theory was propounded, no great straining of the observed facts seemed to be necessary in order to bring them into harmony with it; for the experiments undoubtedly in many cases pointed very nearly indeed to the exact whole numbers, and it is beyond doubt that the tendency of experimenters is to be far too sanguine as to the accuracy which their measurements have achieved. It is easy, after making a number of concordant measurements, to feel confident that the error of the result cannot much exceed the differences between the several measurements; but such conclusions must be accepted with very great caution, for constant errors may creep in which are often hard to detect, and which affect every measurement equally. As a simple example, we may carry out a weighing as often and as carefully as we please; but however

accurate the standard weights may be, and however carefully they may be adjusted to balance the object which is being weighed, the result will be erroneous if there is any inequality in the length of the arms of the balance.

This happens to be a case where the error can be guarded against. It is merely necessary to exchange the weights and the object which is being weighed, and to place each in the pan formerly occupied by the other. The weights should still be equal, and if they are not, the balance is known to be in fault. But there are many cases in which such errors may occur, and where it is almost impossible to foresee them.

The process of taking a large number of measurements affords no security against this. And even when different methods are used, there may be constant errors affecting them both to something like the same extent; this produces an apparent concordance, which gives false confidence in the accuracy of the result.

It became, then, necessary to make a most searching investigation of the exact values of the atomic weights, in order to arrive at certainty. This task was undertaken by Stas, and, as the result of the labours of a lifetime, he came to the conclusion that the law of whole numbers was not in accordance with fact. The most decisive case was that of chlorine, which came out almost half-way between two whole numbers—thirty-five and thirty-six.

But when this has been admitted, it remains a fact that the majority of the atomic weights *are* very near whole numbers. It has been often thought that this must be the result of chance. But there is reason to feel practically certain that such is not the case. We can calculate, by the theory

of probability, the chance that the numbers, if assigned purely at random, should, on the average, deviate so little from whole numbers as they do. A calculation of this kind has been made by the author. The methods of calculation are not suited to a popular book. But the result was to show a chance of something like a thousand to one against the deviations from whole numbers being so small as they are, if they were governed by nothing but chance.

This, then, gave a very good reason for concluding that there was some intimate connection between the atoms of different elements, though it was, and, of course, in large measure still is, impossible to say what the nature of that connection might be.

This was not the only reason for suspecting that different elements might, in reality, have a common origin in spite of the failure of all experimental attempts to break down the barrier between them. The most important generalisation, known as the Periodic Law, pointed strongly in the same direction.

This law is not of sufficient precision to easily admit of simple and definite statement. But, broadly, it is this. Let us make a list of the elements in the order of their atomic weights. Let us also tabulate the value of some other measurable quality of the element such as the melting point, the boiling point, or the refraction equivalent.

We shall then find that the properties of the element do not increase regularly with the atomic weight, but they show a regular fluctuation. Every eighth shows a return to the properties of the first.

The best and clearest example of this is found, not in the properties already mentioned, but in the atomic volume of the element. The late Professor

Lothar Meyer of Tübingen was the first to draw attention to the striking periodicity of this property.

The atomic volume of an element is defined as the quotient of the atomic weight by the density. If we take quantities of the different elements in the solid state, proportional to their atomic weights, then it is evident that these quantities will each contain an equal number of atoms. Thus the volumes of these

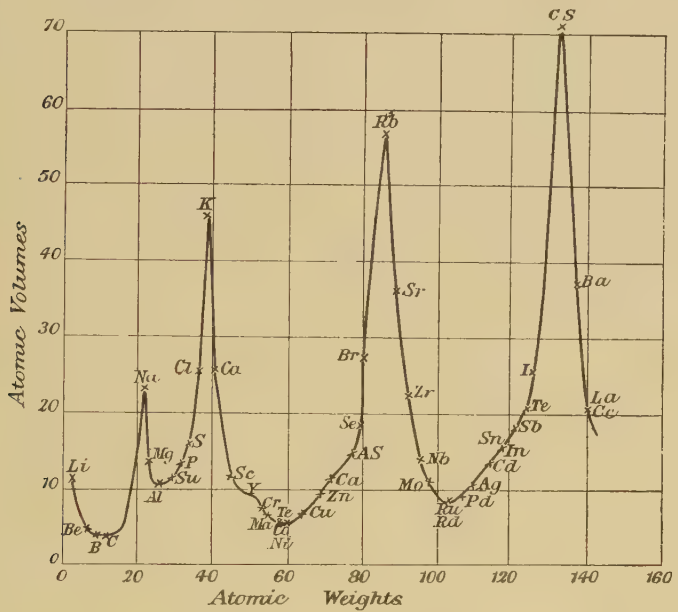


FIG. 26.—Meyer's curve, showing dependence of atomic volumes on atomic weights. Horizontal distances represent atomic weights; vertical ones atomic volumes. Each element is denoted by its chemical symbol. The atomic volume alternately increases and diminishes as the atomic weight increases. The elements of very high atomic weight are not included, for there are so few of them that the further course of the curve is not clearly indicated.

quantities are in the same ratio as the volumes occupied by their respective atoms. The volume is found by dividing the mass by the density.

The quotients of the atomic weights by the respective densities are in the same ratio as the volumes of their atoms, though, of course, not equal to them. We cannot determine the volume of an atom

absolutely by considerations of this kind. But we can compare the volume of one atom with that of another.

It is found that where the atomic volumes are exhibited on a curve, as dependent on the atomic weight,[1] that the curve goes through a regular series of periodic fluctuations. A curve of this kind is given in fig. 26.

The position for each element is indicated by its chemical symbol. The maxima of atomic volume always occur at the alkali metals, lithium, sodium, potassium, rubidium, and caesum. This curve is sufficient to show at a glance that the elements are not entirely independent and isolated from one another, but that they all form part of one common scheme.

The periodic law, though eminently suggestive, has proved in some respects disappointing. It might be thought that the discovery of this relation would lead to the foundation of exact numerical laws connecting the atomic weights of the elements, which would be able to survive the most searching experimental test—laws which would inevitably suggest the true structure of chemical atoms and their mutual relations. This has not proved to be the case. It has been found that there are exceptions and irregularities which make it impossible to accept the periodic law as more than a rough approximation to the truth.

Thus, for example, it is necessary, in order to put the element tellurium into its proper relation with the kindred elements, oxygen, sulphur, and selenium, to assign it a place before iodine in the list of the elements. If this were not done, tellurium, and iodine

[1] On just the same principle as the height of the barometer is exhibited as dependent on the time by the trace drawn by a self-recording barometer.

too, would be thrown into a position in the periodic table altogether inconsistent with their known chemical behaviour. Most careful experiments, however, have made it certain that the atomic weight of tellurium is slightly higher than that of iodine. It seems most probable that some disturbing cause exists which modifies the atomic weights, not indeed to such an extent as to altogether obscure their mutual relations, but enough to deprive these relations of numerical exactness.

The problem of the evolution of the elements is one of the most interesting and fundamental that science presents. Although little definite progress has yet been made, the door seems to be open; and the author, for one, feels little doubt that the processes of radio-active change which have been observed to take place in a few instances, are in reality representative of the evolution of all the elements.

The information which we possess as yet about the ultimate products of the degeneration of radium is very imperfect. It will be remembered that the α-rays consist of heavy particles whose mass was found by the rough measurements which were alone feasible, and by certain plausible assumptions, to be intermediate between hydrogen and helium. It is doubtful whether the measurements are good enough to make it certain that the α-particles do not consist, on the one hand, of hydrogen, or, on the other, of helium. The point must remain open for the present. But considering the fact that helium has been observed to be formed in radio-active processes, the balance of evidence seems to be greatly in its favour.

These α-rays are thrown off by every radio-active body, and the probability is that the particles are in each case the same. It is true that there is some difference of penetrating power in the various cases; but these are reasonably attributable to varying velocities.

If this view is correct, all the radio-active bodies must be giving off the material constituting the α-particle, whether it be hydrogen, helium, or something different from either; there is no means of telling whether non-radio-active products are generated as by-products at each stage of the radio-active change. We do not know, for instance, what happens when the radium atom gives off one or more α-particles. Does this suffice to convert it wholly into atoms of the emanation, or is some other inactive substance produced simultaneously? The quantities of material are too small to enable the question to be answered.

It will, perhaps, be objected that if helium has been looked for and found, it is only necessary to apply the same methods in searching for anything else, and that a decisive answer could in that way be at once obtained.

Helium, however, is a substance which can be detected spectroscopically in extremely small quantities. It is doubtful whether any other substance is known, with the possible exceptions of sodium and hydrogen, which lends itself so well to spectroscopic identification.

The reasons for this may easily be explained. In the first place, helium is a gas, and moreover, a very light gas. So that to charge a small Plücker tube with it at a very low pressure, requires a very small quantity indeed, by weight. In the next place, the gas is brilliantly luminous under the electric discharge; and the luminosity is concentrated very largely in one line, the yellow line D_3, whose position in the spectrum is easily identified by reference to the soda lines. This brings us to another point. There are other substances, such as sodium and hydrogen, whose spectra are conspicuous with very small quantities, but these substances are to be met with everywhere.

It is, for instance, very difficult, if not impossible, to prepare a Plücker tube so free from moisture that the characteristic red line of hydrogen cannot be seen in it when the electric discharge is passed; so that it would be very difficult to infer the production of hydrogen from radio-active substances from the presence of this line. But with helium it is far otherwise. For helium is very sparsely diffused over the earth's surface, and in the atmosphere. And it is very unlikely, indeed practically impossible, that any helium which is observed should have accidentally gained admission to the tube.

The majority of the elements do not lend themselves very easily to spectroscopic detection, when only traces are present. Oxygen, for instance, gives very little luminosity, and its spectrum is not at all conspicuous or easily identified.

The metals of the alkalies and alkaline earths are in some cases easily detected. If any of these occur in the products of radio-activity, it may be possible to detect them. But here again, sodium, which gives the most easily visible spectrum, is so universally present in everything, that it would be difficult to draw any conclusion from its appearance.

There is another direction in which we may hope to gain information as to the connection between the elements.

We have seen that radium is gradually evolving the emanation. Now, if there is any law of nature which experiment has placed on a firm basis, it is the law of the conservation of mass. Nothing we can do to any portion of matter will in the smallest degree affect its weight, so long as nothing is allowed to escape from it. When any apparent exception to this law has turned up, it has always been traced to a misinterpretation of the facts. Take for instance the case of a

burning candle. What has become of the weight of the candle when it has all burned away? Experiment shows that the constituents of the candle have combined with the oxygen of the air, and have remained in a gaseous form in the air. If we burned the candle in a closed globe, the globe would be found to weigh just as much after the candle had burned away as it did before. And the same thing is found in every case.

It is true that a transmutation of the elements is a matter beyond the range of ordinary experience, and that it is perhaps rash to feel absolutely confident that the law of conservation of mass which has been deduced from ordinary experience applies to such a case. The law, however, has become so firmly established in the minds of scientific men, that the burden of proof must lie with those who doubt it.

Assuming, then, that the law holds good, radium which has generated emanation must weigh less than at first. In other words, the radium is gradually wasting away. Recently an experimental determination has been made of the rate at which the emanation is generated. Sir William Ramsay and Mr. Soddy have measured the volume of emanation yielded in a given time by a known weight of radium salt. Now, as we have seen (p. 118), the density of the emanation is approximately known. Knowing the volume and the density, the weight follows; so that we know what weight of emanation is yielded by say a gramme of radium in a day. It is evident that we can find, by calculation, how long it takes for half the radium to turn into emanation, if we assume that that is the only immediate product. The result is to show that this process occupies something like a thousand years. We cannot, of course, say how long it would take for the whole of the radium to change to emanation, for

the process gets slower and slower, and does not come to a definite end. But, practically, we may say that radium cannot survive more than a few thousand years. If another product is produced simultaneously with the emanation, the life would be still less.

Other arguments, of a less direct character,[1] into which we shall not here enter, point to about the same figure.

How then can it be that any radium has survived? For it is very certain that the earth was in existence in much the same condition as at present, many millions of years ago. Any radium which formed part of its original constitution must have long since degenerated. It would not have survived till now. There is no alternative but to conclude that radium is being in some way called into existence.

As before remarked, we cannot postulate the creation of matter unless we are driven to it by the clearest necessity; so we must suppose that some other elementary substance is being constantly transformed into radium.

The only question is, What is the parent substance? We have not far to seek for a plausible answer. Uranium is contained in all, or nearly all, the radium-bearing minerals. And uranium is radio-active, and therefore necessarily itself undergoing change. Is it not reasonable to assume that uranium is changing into radium? This view is due to Professor Rutherford and Mr. Soddy, and has much to recommend it. We learned (see p. 126) that uranium was constantly changing into a substance which has been called uranium *X*. We saw also that the latter gradually lost its radio-activity. In saying this, all that is meant is, of course, that the activity becomes very much less than at first—so much less that experiment fails to

[1] For an account of these, see Professor Rutherford's *Radio-activity*.

detect any activity with the quantity which has been used in the tests.

But it must be remembered how very small that quantity is. The amount of uranium X obtained is too small to be detected at all by any test but its intense radio-activity. It is doubtful whether it would be visible under the microscope, if unmixed with foreign matter. The activity of uranium X, therefore, *while it lasts*, must be very great, even when compared with that of an equal quantity of radium. So that the radium produced by the decay of uranium X might easily be too little for detection; the apparent inactivity of decayed uranium X is accordingly no serious objection to the view that uranium may be slowly degenerating into radium, through the intermediate stage of uranium X, and perhaps other intermediate stages.

Many considerations render this explanation of the origin of radium plausible.

The weight of the uranium atom is greater than that of the atom of radium. This is consistent with what happens in other cases of radio-active change. For we know that the atom of the emanation is lighter than that of radium, and that the atom of helium is lighter than that of the emanation. The tendency is always towards a lighter atom. Nor could it well be otherwise, when the process of change is accompanied by the expulsion of α-particles from the atoms, and consequent diminution of their weight.

There are many minerals which contain radium; Mr. Boltwood, and also the author, have recently investigated these with a view to determining whether uranium and radium always occur together, and also more particularly, whether they are always present in the same proportion. The result has been to show that this is approximately so. This fact is

strongly confirmatory of the view that uranium is the parent of radium. Since the life of radium is a few thousand years, and since the mineral is much older than that, it would be expected that the quantity of radium present would have reached an equilibrium value, when the rate of production is equal to the rate of decay, just as the emanation from a given quantity of radium reaches an equilibrium value. This equilibrium quantity of radium would of course be in proportion to the amount of uranium producing it. That is exactly the state of things which analysis of the various minerals seems to reveal. Mr. Soddy has also made direct experiments to see if he could actually observe the growth of radium from uranium. He has not succeeded in doing so, and the fact that he has not is somewhat disturbing; for according to the anticipated rate of production of radium, its formation should have been easily detected. The most probable explanation of this failure is that the uranium *X* has to go through some intermediate stage, before turning into radium. It is probable that thorium, polonium, and actinium are also members of a connected series of radio-active products. Thorium occurs in some cases in the entire absence of uranium, as in the minerals aeschynite and monazite, so that there is no reason at present to connect it with the series of products of which uranium is the parent. Polonium and actinium, on the other hand, do occur with uranium in pitchblende. Whether they ever occur in the absence of uranium is a question which has not yet been investigated.

The case of polonium, in particular, would seem easy to attack. We know that polonium only retains its activity for a few years; or, at all events, that after a year it is much less active than at first. This makes it certain that polonium must be quite rapidly

formed in pitchblende; for there is relatively a good deal of it present, and a considerable supply must be yearly formed, to make up the yearly loss. It would seem a matter of no great difficulty to ascertain experimentally which of the constituents of pitchblende is responsible for the formation of polonium.

It has been suggested by Professor Rutherford and Mr. Soddy that the residual activity from the active deposit of radium, which remains after the bulk of the activity has decayed, is due to polonium. An objection to this view is that the material gives off β-rays, while polonium only gives α-rays. But that may be due to the presence of some other radio-active constituent as well as polonium. It will be necessary to wait for data as to whether this activity decays at the same rate as polonium or not.

If the views explained in this chapter are adopted, it would follow that we must regard the intermediate products, such as the emanations, and the active deposits, as belonging to the same class of substances as the 'permanent' radio-active elements. The difference is only in degree. The durable radio-active elements are feebly active—considering the large quantities involved. The intermediate products are intensely active, but their activity is of short duration. The total amount of radiation which the product emits during its whole life is perhaps in many instances not very different in the two cases. But it is difficult to formulate any precise view, when we consider the complication introduced by the existence of the β- and γ-radiation, as well as the α variety. It will now be realised that we have good hopes of being able eventually to thoroughly understand the mutual relations of the elements. The veil which has hitherto shrouded the mystery of their separate existence has to a very slight extent been torn aside.

The number of elements which have hitherto been recognised as taking part in the scheme of radio-active change is very small. This may partly be due to the difficulty, so often insisted on, of recognising the presence of minute traces; but there are other possibilities.

Helium is one of the products of the series of changes connected with the existence of radium.

Now helium is only one of a series of five gases, all having a graduated series of properties. These gases have several times been mentioned in the course of the present work. But it will be desirable here to give a somewhat more detailed account of them. The complete series is

helium, neon, argon, krypton, xenon.

We have already devoted some consideration to the history of the discovery of argon, and of the discovery of helium which resulted from it. As soon as these gases had been obtained, the question arose of whether they were simple homogeneous substances, or mixtures of two or more constituents.

Suppose we possessed a liquid of unknown composition. How should we ascertain whether it was homogeneous or complex? Whether it consisted of one chemical substance or of several? The method which generally succeeds is to distil it. Unless the various constituents happen to boil at exactly the same temperature (and this would be most unlikely) the liquid first collected from the distillation would be rich in the more volatile constituent, and by redistilling this product several times we could eventually obtain the volatile constituent in a freer state. The process is quite a familiar one. For it is employed for separating pure (or at least strong) alcohol from fermented liquor, as well as for numberless other technical purposes.

This is exactly the method which has to be employed for separating the constituents of crude argon. Argon being a gas, it has to be cooled to a very low temperature to make it liquefy. This can be done by a suitable use of the cooling agency of liquid air. The liquid argon has then to be distilled. This is done by allowing the temperature to rise slightly. The liquid then boils off again into the gaseous form. It was found by Sir William and Dr. Travers that the first portions of argon which distilled off contained traces of a lighter gas, to which they gave the name neon. The dregs of the liquid argon, which boiled off last, were found to contain two new heavy gases, which were called krypton and xenon. The three new gases were finally, after many distillations, obtained in a pure state, though in very small quantity, for the proportion in which they exist in argon is very small. By far the greater part of the crude argon of the air consists of true argon. The neon, krypton, and xenon are mere impurities. A trace of helium is also present.

Helium has never been liquefied, and so it has not been feasible to ascertain by distillation whether it contains traces of anything else. But the probability is that it does not. The new gases, neon, krypton, and xenon, have all been found to resemble argon and helium in their inertness, and in other properties which it would be beyond our limits to describe. The five gases form a series of increasing density and decreasing volatility.

We have seen that helium is produced in the degeneration of radium. Is it not probable that the other gases have had a similar origin? That they too have had their origin in radio-active substances? It is natural to inquire whether any of the gases

besides helium are found in minerals. So far as the author is aware, there is only one such case. A rare Norwegian mineral called malacone, which is a variety of zircon, has been found to contain traces of argon, as well as helium. This substance has been tested, and found to possess marked radio-activity. This was natural, for the mineral contained helium also, and, no doubt, radium. The mineral was heated, and the emanation extracted from it. But this emanation was found to decay at the same rate as the emanation of radium. So that, if there is a radio-active substance present in the mineral, which has produced the contained argon, it does not seem likely that it produces a characteristic emanation. It may be that the radio-active change which produced the argon is over. That the activity has exhausted itself, or it may be that it still exists in the mineral, but gives no emanation. The question deserves further investigation, but the mineral is difficult to procure, and the proportion of argon contained very small.

Upon the whole, the probability is that the substances which have produced the other inactive gases no longer survive. Those which produce helium, an extreme member of the series, are probably alone in existence at the present time.

The activity of radium stands in remarkable contrast to the inactivity of the chemically allied metals, barium, strontium, and calcium. It must be remembered, however, that the number of molecules which are taking part in the change, at any given instant, is but a very small fraction of the whole. The radium, we believe, takes thousands of years to decompose altogether; and the decomposition of an atom, or at least the expulsion of an α-particle, must be quite a sudden catastrophe. So that the

proportion of atoms which are in the act of decomposing at any given moment is very small. The decomposition must be the result of a conjunction of circumstances within the atom which is of extremely unlikely, and consequently rare, occurrence. What those circumstances are, we do not yet know. From this point of view, it will not be difficult to understand that what is a very rare event in the case of a radium atom, may be much rarer still in the case of an atom of the allied metals, so rare, in fact, that it may never occur at all within human experience. So far, after all, the absence of radio-activity does not necessarily imply any great structural difference between the two kinds of atoms.

With regard to the elements not recognised to be radio-active, there are several remarks to be made. In the first place, as we have seen, every obtainable material shows some traces of radio-activity. But there is difficulty in feeling sure that this is not due to traces of radium contained in it as an impurity. For different samples of the same substance seem to differ very greatly in activity. One piece of tinfoil, for instance, may give double the radio-active effect of another.

Still, it is possible that some of the activity is really due to a specific property of the element in question.

We have seen that in some cases, inactive products are formed by radio-active change, which themselves yield radio-active products by further change. This occurs in the course of degradation of the active deposits of radium and thorium. Professor Rutherford has very aptly remarked that the ordinary inactive chemical elements may represent such inactive phases, and that they may, none the less, be

undergoing changes of the same nature as those in progress in the active elements, in spite of their want of radio-activity. It is the absence of the latter that prevents the detection of the changes.

Our best chance of obtaining further knowledge on this question is to collect careful statistics of the occurrence of different elements in minerals, and, in particular, to ascertain whether there are cases when elements are invariably associated, and never found separate.

Even if such cases cannot be found, it will not tell much against the theory. For, if the changes are very slow (and we know nothing to limit their possible duration), time enough may have elapsed for the element produced to have been separated from its parent by the course of geological changes.

The question may be raised, Is it possible to stimulate a substance ordinarily inert, so as to make it radio-active? It is difficult to give a satisfactory answer, but some experimental results have been published which seem to suggest that it is possible. M. Villard found that bismuth, exposed for some time to the cathode rays, became temporarily radio-active. The experiments, however, require confirmation.

Quite recently, Sir William Ramsay has obtained evidence that the radium rays are able to develop activity in a material separated from the radium by an air-tight partition. It was found that the walls of a glass beaker, in which a closed bulb containing radium solution had been kept for a year, had become active, and gave off an emanation of very quick decay, resembling that of actinium. Further developments of this important observation will be awaited with keen interest. There seems to be a rich field for investigation, more particularly

with reference to the effect of the rays on different substances.

Thus, it is possible that the actinium extracted from pitchblende is a substance rendered active by the neighbourhood of radium, or by exposure to its radiation. We do not yet definitely know. It may have been made active by the cathodic bombardment at close quarters by the β radiation of the active deposit.

On the other hand, the absolute constancy of the rate of decay of the emanation, and other temporarily active products, in spite of any change of conditions to which we can expose them, seems to point to the conclusion that the course of radio-active change is beyond the range of human control.

It is unsatisfactory to be unable to make more definite statements. But the present state of our knowledge does not warrant them. The question of whether it will be possible to induce radio-activity artificially may be in the future one of no slight practical importance. For, if this could be accomplished on a sufficient scale, it might be practicable to set radio-active changes going which would result in the formation of the precious metals. This is but a dream at present. But it is not too much to say that modern science has brought us a stage nearer to the possibility of its fulfilment.

CHAPTER VIII

THE ELECTRICAL THEORY OF THE NATURE OF MATTER

In this concluding chapter we shall consider, in the light of radio-active phenomena, the nature of the chemical atom, and the circumstances under which it may be expected to break up.

The old-fashioned view of chemical atoms was that they consisted of elastic spheres, of uniform structure, or rather want of structure, within. In the light of present knowledge, so simple a theory is altogether untenable. We have seen that the atoms of radio-active elements are able to emit small particles or corpuscles of about $\frac{1}{1000}$ of the mass of the hydrogen atom, the lightest atom known. They are also able to emit positively charged particles, comparable in mass with the hydrogen atoms. It is also nearly certain that each atom of radium, for instance, emits in the successive processes of degeneration into the emanation and active deposit several of these positive masses. It cannot, therefore, be doubted that the atom of a radio-active substance is a structure of great complexity, very different to the simple elastic sphere.

Since electrically charged particles are sometimes emitted from the atom, it is inferred that the atom is built up of such particles, which, in ordinary cases, are in equilibrium under the influence of their mutual attractions and repulsions, and of centrifugal forces.

There is every reason to think that the negative electrification resides in all cases on corpuscles, of the same kind as those which are expelled, and which constitute the β-rays.

These negative charges are assumed to be held in equilibrium under the influence of positive electrification; how this positive electrification is distributed it is very difficult to decide. No case is known in which positive electricity is associated with a corpuscular mass. No positive corpuscles, complementary to the negative ones, have ever made their presence apparent. Whenever we obtain a positively charged particle, it is always attached to a comparatively large mass. So that there are considerable objections to the assumption that positively charged corpuscles exist in the atom. It may be that they are there, but that the processes which succeed in detaching an isolated negative corpuscle are not able to detach the positive one.

Recently it has been preferred to suppose that the positive electrification is not localised in particular spots in the atom, but that it is diffused uniformly over a considerable volume. The negative corpuscles are assumed to be immersed in this positive fluid, as it may be called.

It would be idle to pretend that this theory constitutes an ultimate explanation of the nature of the atom. In some ways it leaves this question more mysterious than ever. The assumed positive volume electrification which does not reside on matter presents at least as formidable a problem as matter itself appeared to do in the first instance. That, however, is no reason for rejecting the theory, if it is found to give a satisfactory explanation of the facts.

We have already seen, in discussing Kauffmann's observations on the corpuscles, travelling with speeds

approaching that of light, which radium emits, that there is good ground for believing that the mass of corpuscles is due entirely to the charge of electricity which they carry. Now, since it must be admitted that mass can originate in this way, it is well to consider whether it is necessary to postulate any other kind of mass. For evidently it is undesirable to assume that some unknown kind of mass exists, until it is quite clear that the electrical kind, whose nature and origin we do to some extent understand, is inadequate to fulfil all necessary requirements. It is unphilosophical to assume two kinds of mass, if one kind can be made to do.

The most important condition which any adequate theory of mass must satisfy is that the mass is altogether independent of the state of aggregation or chemical combination of the material. For it is found by the most careful experiments that the mass of a chemical compound is exactly the same as the sum of the masses of its constituents. Thus, for instance, the mass of water is exactly the same as the combined weight of its constituent gases, oxygen and hydrogen.[1]

The electrical theory, properly interpreted, gives a satisfactory account of the conservation of mass. The question to be faced is this. Assuming the atom to consist of corpuscles embedded in a volume of positive electrification, can the electro-magnetic inertia of each corpuscle be independent of the neighbourhood of other corpuscles?

Now the electro-magnetic inertia of the corpuscle is due to the generation of a magnetic field by the lines of

[1] Some recent experiments by Heidweiler should be mentioned, which have led him to conclude that a slight change of weight does occur on chemical combination. But these have not yet been confirmed, and it is impossible to accept so revolutionary a conclusion until other experimenters have been over the same ground with concordant results.

electric force which radiate out from it in all directions. By far the greater part of the energy which this magnetic field represents is localised in the space very near the corpuscle, where the lines of electric force are very crowded. The effect of bringing other corpuscles into the neighbourhood of the one we are considering will be to disturb its electrostatic lines. This disturbance, however, will only affect the lines at some distance from the corpuscle from which they spring, unless, indeed, the other corpuscle comes to very close quarters. The mutual repulsion of similar charges will prevent that happening. So that the lines of electric force in the immediate neighbourhood of a corpuscle are secure from disturbance, and the magnetic field in these regions, which represents almost all the energy of motion, is not liable to be affected. Thus, the mass of a corpuscle, if of electrical origin, will not be affected by the presence of other corpuscles. The mass of the atom, however, is to be regarded as the sum of the masses of the constituent corpuscles. That is accordingly nearly independent of the presence of other atoms. It would be very interesting if the slight changes of weight which some experimenters have thought that they could detect in chemical combination, could be traced to the change of distribution of the electric field of the corpuscles of one atom by the presence of another.

The mass associated with an electric charge depends on the extent to which the charge is concentrated. If the charge resides on a sphere, for instance, the mass is greater if the sphere is small than if it is large. Since the positive electrification is assumed to be much less concentrated than the negative, it does not contribute appreciably to the mass of the atom.

We know the charge on a detached corpuscle, and its mass. If the mass is wholly electrical, these data are sufficient to determine how large the sphere on which the electricity resides must be. The result is that the diameter is about 10^{-13} cm., or one five-million-millionth of an inch.

The size of a chemical atom is commonly estimated at something like 10^{-8} cm., or one fifty-millionth of an inch, so that the diameter of a corpuscle is no more than one hundred-thousandth of that of an atom. There are in a hydrogen atom something between 500 and 1000 corpuscles. Thus the corpuscles are very sparsely distributed, being separated by distances which, however small compared with the distances which are within the range of microscopic vision, are enormous compared with the dimensions of the corpuscles themselves. The corpuscles in an atom are of something like the same degree of scarcity as the planets in the solar system. That is, the distances between them bear the same kind of relation to their own size. This being so, it is not at all surprising that the corpuscles emitted by radio-active bodies—the β-rays, that is—are able to penetrate enormous numbers of atoms; for they can readily go straight through an atom without serious danger of collision with another corpuscle. We assume that the positive matrix of the atom is freely penetrable by the corpuscles of the atom itself, or by external ones.

On this theory an α-particle consists of a part of the positive nucleus of the atom torn off it, with nearly the proportionate number of corpuscles. Since, however, the α-particle is positively charged, we must assume that it has one corpuscle short of the full number. Thus there would be a surplus of positive electrification, as experiment shows that there is.

The penetration of solid materials by the α-particles presents a more formidable problem than the penetration by β-particles; it is not, however, by any means impossible that our entire system of corpuscles, representing an α-particle, might pass through another, representing an atom of ordinary matter, without either of them being permanently affected. If we remember that the α-particles move with a velocity which is not beyond measure less than that of light, it will be evident that the corpuscles in the α-particle have not much time to perturb those in the atom through which it passes, or to disturb their equilibrium. Collisions, however, are naturally more frequent when a complicated system of corpuscles passes through an atom than when a single one only does so. Thus the α-rays are naturally more easily absorbed than the β-rays, and are not able to get so far through matter.

Little has yet been said about the forces which hold the corpuscles in position in the molecule. The positive matrix in which the corpuscles are immersed will attract them to its centre. On the other hand, they will be repelled electrostatically from one another. There might, indeed, be static equilibrium under forces of this kind. But on such a view it is difficult to understand how there should be any element of instability in the atom, such as might account for the phenomena of radio-activity. Moreover, stationary clusters of corpuscles could not emit vibrations with characteristic periods, as the atom does in yielding a spectrum. It is believed, therefore, that the corpuscles in an atom are in a state of rapid rotation about the centre. This view would strengthen the analogy between the constitution of an atom and that of the planetary system, to which attention has already been drawn.

To deal by direct calculation with systems of 1000 corpuscles, which might be distributed anyhow in three dimensioned space within the matrix, would probably be impracticable. By dealing with a moderate number of corpuscles, however, whose movements are assumed to be confined to one plane, Professor J. J. Thomson has obtained results which illustrate in a general way the manner in which the more complicated systems of real atoms are likely to behave. In particular, he has found that certain configurations recur periodically as the number of corpuscles is continuously increased. This seems very consistent with the observed properties of atoms, as expressed by the periodic law.

It is probable that the rotation of corpuscles in the atom is the cause which gives rise to light vibrations. We know that light waves travel with the same velocity as electrical ones, and no one now disputes the identity of these two kinds of waves. The only difference between light waves, such as are radiated by atoms, and the electric waves used in wireless telegraphy, is in their length from crest to crest. The length of the light waves is something like a forty-thousandth of an inch; the length of the electrical ones many yards.

Now the rotation of a corpuscle in a circular orbit round a central positive charge involves a rapid reversal of the electric field along the radius joining them. For when the corpuscle has gone round half the circle, the electric force, which was, say, northwards to begin with, is now southwards. After a whole turn it will, of course, be northwards again.

This rapid alternate reversal of electric force is just the condition for sending off electric waves. The waves, for instance, which are used in wireless telegraphy, are produced by the surging of a charge of

electricity to and fro in an oscillatory spark between two knobs. The direction of the electric force is thus reversed with great rapidity.

This case of a single corpuscle going round in a circle is the simplest that can be taken as an example. But the same general principle applies to the actual case of many such corpuscles, with complex movements and mutual perturbations. It will be understood that the corpuscular atom is quite a sufficiently complicated structure to account for the complexity of the vibrations which most atoms give out, when these vibrations are analysed and sorted out according to their wave lengths by means of the spectroscope.

It may, perhaps, be thought that we have got very far from the simple facts of radio-activity in applying the theory of corpuscles to the spectrum of an atom. There is, however, a very direct proof that they are concerned in this phenomenon. It was discovered by Zeeman in 1897 that the spectrum of sodium was modified by placing the radiating material under the influence of intense magnetic force. The lines were broadened, and as closer observation had shown, split up into three or more components. Though this effect is very inconspicuous and difficult to observe, it is an observation of far-reaching consequences. We know that the motion of a corpuscle is modified in a magnetic field, and its period of vibration altered accordingly. Thus the Zeeman effect gives quite a direct proof that corpuscles are concerned in the mechanism of radiation. The amount of effect, indeed, enables an estimate to be made of the ratio of the charge of a corpuscle to its mass; the result is quite in accordance with the measurements made on the corpuscles of radium, or of the cathode rays.

A few words must be said on the difficult subject of what causes the rupture of an atom and the

expulsion of a corpuscle or α-particle with great velocity.

Sir Oliver Lodge has pointed out that if the normal condition of the corpuscles is one of rotation, this must be accompanied by the emission of energy in the form of electric waves. We have already given the reason for this. Now it is evident that an atom cannot go on indefinitely giving out energy; sooner or later the supply which it contains must fail, and when that happens some catastrophe in the atom may be anticipated. Sir Oliver Lodge considered the case of a single electron revolving outside a positive charge distributed over a considerable volume. As the energy of motion diminishes owing to loss by radiation, the corpuscle will get nearer to the centre. In this position its velocity is necessarily greater than before. The speed may increase until the velocity of light is approached, when, as we have seen (see p. 72), the mass will begin to increase also. When this happens, the whole balance of forces may not improbably upset, and the corpuscle may escape with the velocity it has acquired. The fact that the corpuscular velocities observed with radio-active substances are of this order is favourable to such a theory. It is difficult to believe that such a velocity could be suddenly acquired in the process of expulsion. It seems at least clear that no atom in which the corpuscles are rotating can be permanent.

An obvious difficulty is that substances distinctly radio-active are so exceptional; for this theory seems equally applicable to the case of any atom. It may be remarked that we have a millionfold descent in radio-activity when passing from radium to uranium; while experiments which have been already considered (see p. 149) render it, to say the least, possible that ordinary substances may possess an activity of their

own, apart from radio-active impurities, which is much more than a millionth that of uranium. What the difference of atomic structure may be that causes so profound a difference in radio-activity must be left to the future to say.

APPENDIX A

EXPERIMENTAL NOTES

A FEW practical hints will be given for the benefit of those who may wish to observe for themselves the phenomena of radio-activity. The experiments considered will only be those which can be conducted without much difficulty or expense, and with simple apparatus.

It cannot be too strongly recommended that some of the experiments should be attempted; for they will give an insight into the subject and an interest in it which mere reading can never give.

For most of the experiments, some radium will be required. This may now be purchased from the majority of instrument makers; advertisements of radium and other requisites for experiments on radio-activity (such as fluorescent bodies) are to be seen in the scientific journals, notably in *Nature*. Five milligrammes of pure radium bromide is a useful quantity. Such quantities are sold for about £5, though the price fluctuates very much at present. The salt is usually sold in a small capsule, which has a removable lid; for most of the experiments the lid is best left on.

If it is not desired to spend so much on the salt, the experiments can be performed with an inferior product, containing only a moderate or small percentage of pure radium. This is much cheaper, but of course the effects are less brilliant. It will be difficult to perform the experiment on magnetic deflection with very inferior material. The photographic experiments generally will, of course, require longer exposures if this is used.

EXPERIMENT 1

Photographic action of Radium

To illustrate the photographic effects of radium, and to show

that metals are more absorbent for the radium rays than other substances, a 'radiograph' may be taken of metal objects in a wooden box, or of coins in a purse. This is on the same principle as those taken by the Rontgen rays, though, as has been already explained, the results are not so clear.

Put a photographic plate in a black envelope. Lay the object, say a purse with coins in it, on the film side, and put the radium some inches above so as to radiate on to it. Leave this arrangement for some time—twenty-four hours will probably not be too long, but this must be found by trial. The further away from the plate the radium is placed, the clearer will be the results; but a longer exposure must, of course, be given at an increased distance.

Experiment 2

Photographic action of the Salts of Thorium

The radio-activity of thorium salts can be tried by a simple experiment devised by Mr. Richard Kerr. He uses one of the mantles for the Welsbach incandescent gas-burners, which can now be procured anywhere, and which contain thorium. Take one of these mantles and cut it open with a pair of scissors, so that it can be spread out flat. A new mantle must be used, which has not been fired, for after that it becomes too brittle to be touched. Spread out the mantle on the film side of a photographic plate, and lay another glass plate on the top, so as to keep it flat. Leave the whole in a light tight box in a drawer or cupboard for at least a week. After that time has elapsed, take the plate out and develop it.

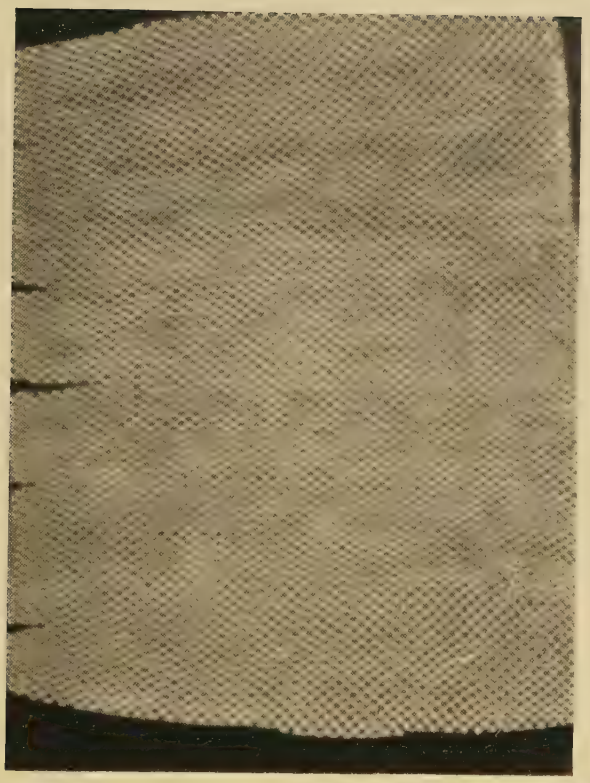
A very clear picture of the mantle will be obtained, showing the network black on a light ground. A print from this will, of course, more clearly represent the appearance of the mantle itself, for the network will then be white on a dark ground.

Experiment 3

Photographic action of Pitchblende

Obtain from a mineral dealer a piece of pitchblende, selecting for preference a piece which contains other minerals, such as quartz, felspar, and pyrites, embedded in it. Have one surface of the piece cut flat and polished. This can be done by an amateur, but practically it will save time and money to

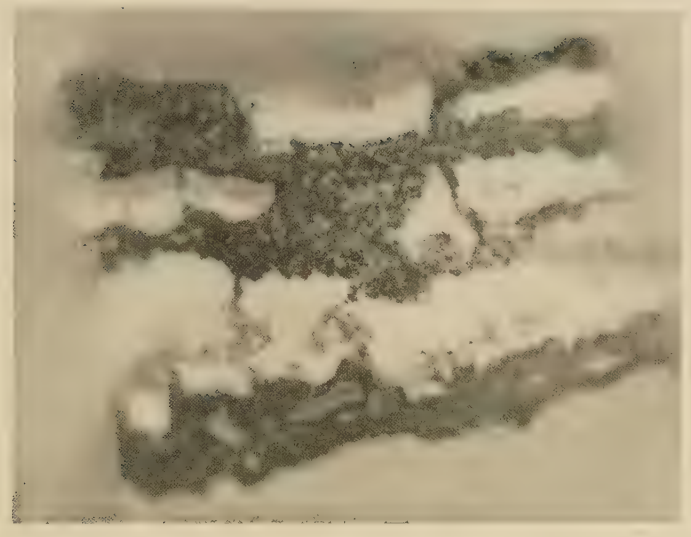
PLATE I.



PHOTOGRAPH OF A WELSBACH INCANDESCENT GAS MANTLE, TAKEN BY MR. RICHARD KERR.

THE MANTLE WAS OPENED OUT AND LAID FLAT ON A PLATE. THE EXPOSURE LASTED FOR EIGHT DAYS. THE THORIUM CONTAINED IN THE MANTLE MAKES IT RADIO-ACTIVE, AND ENABLES IT TO ACT ON THE PLATE.

PLATE II.



PHOTOGRAPH OF A PIECE OF PITCH-BLEND, TAKEN BY ITS OWN RADIO-ACTIVITY.

THE PLATE WAS SIMPLY LAID IN CONTACT WITH THE PITCH-BLEND SURFACE FOR A WEEK AND DEVELOPED. THE PITCH-BLEND SHOWS DARK; THE ASSOCIATED MINERALS, FELSPAR, ETC., WHICH ARE NOT RADIO-ACTIVE, SHOW LIGHT. SLIGHT DARKENING CAN BE SEEN OUTSIDE THE LIMIT OF THE PITCH-BLEND; THIS IS DUE TO BECQUEREL RAYS FROM THE SIDES OF THE SPECIMEN, WHICH FALL ON THE OUTLYING PARTS OF THE PLATE.

PLATE III.

RADIOGRAPH OF A PURSE CONTAINING COINS, TAKEN BY RADIUM.

THE METAL FRAME OF THE PURSE AND THE ENCLOSED COINS STOP THE RAYS MUCH MORE THAN THE LEATHER, SINCE THEY ARE DENSER. THUS IN THE POSITIVE PICTURE THEY SHOW BLACK ON A LIGHT GROUND.

take it to a lapidary, or to have it done by the dealer from whom the specimen is purchased. Lay the flat side on the film side of a photographic plate, or of a piece of bromide paper, placing the whole in a light tight box, which for further security should be placed in a dark cupboard. Leave it for a fortnight; after that time, develop. A picture of the mineral surface will be obtained (Plate II.), the pitchblende showing out as a deep black on the plate, owing to the action of the radio-active materials it contains on the latter. The parts of the film opposite to the associated minerals, felspar, quartz, etc., will be unaffected.

Since pitchblende is black, the direct 'negative' impression will give a better representation of the appearance of the mineral surface than a print from it would do. Thus it is better to use a piece of bromide paper in the first instance instead of a plate.

Experiment 4

Comparative absorptions of different materials

An experiment to illustrate the law that the absorption of different materials is proportional to their density may be made in the following way. Take a piece of sheet iron—tinned iron such as biscuit tins, etc., are made of, will do—cut out with shears, or strong scissors, a piece one inch square exactly. Weigh it, and prepare a piece of wood also one inch square, of the same weight as the iron. This need not be all in one piece, successive layers of thin wood or card may be added to make up the exact weight. Now lay the iron and wood side by side on a photographic plate, which should be wrapped in black paper, or in one of the black envelopes obtainable from photographic dealers. Bring the radium over the whole, at a distance of two or three inches, taking care that its position is symmetrical with regard to the iron and the wood. Expose for a few minutes, or hours, if minutes are found insufficient to give a good impression. This will, of course, depend on the quantity and quality of the radium preparation employed. On development, it will be found that there is intense blackening of the plate where the wood and iron screens do not cover it. Where they do, there is less darkening owing to the partial absorption of the rays. It will be found that the shadows of

the wood and iron screens are about equally dense ; thus showing that equal masses produce equal absorptions, independently of the material used for the absorbent screen.

Experiment 5

Fluorescence produced by the Rays

This is easily observed with a few milligrammes of radium bromide. A fluorescent screen, such as is usual for observing the bones with Rontgen rays, will light up conspicuously when the radium is brought up, either from the front or from behind. In the latter case the rays penetrate the cardboard on which the fluorescent material is spread. Interpose a piece of tinfoil, or other thin metal, and the fluorescence will still be seen, though not so brightly as before. With care, and by remaining in the dark for some time so as to get the eye into its most sensitive condition, the fluorescence may be observed even when fairly thick materials, such as the palm of the hand or a book, are interposed. In this case the γ-rays are chiefly operative.

If the fluorescent screen is not available, the same phenomena may be observed with a diamond. Imitation diamonds may readily be distinguished by their far slighter fluorescence, though they, as well as common glass, are quite visibly luminous. To see the fluorescence of the tissues of the eye, stay in the dark for some time, and when your eyes have become sensitive to feeble lights, shut the eyelids, and bring the radium near to one of them. Most people will easily get an impression of luminosity, though some do not appear to see it very readily. A piece of black paper should be placed over the radium, to avoid any possibility of complication owing to its own feeble luminosity, which, by the way, should be noticed.

Experiment 6

Coloration of Glass by the Rays

Lay a piece of ordinary sheet glass on the cell or tube containing a few milligrammes of radium bromide. In a few days the purple coloration will be quite visible. When feeble it will best be observed by laying the glass on a sheet of white

paper. After the lapse of a few weeks the coloration will be very strong, and of a deep violet colour.

Other substances may be tried also. Fluorspar, of the colourless varieties, can readily be coloured. So can rock-salt, or, if preferred, ordinary table salt. Dissolve the coloured salt in a little water, and you will find that the solution is colourless; boil it down, in a small porcelain basin over a spirit lamp, and the salt, when dry, will be colourless as at first.

Experiment 7

Electric Discharge by Radium

This is as easy an effect to observe as any. Any electroscope will serve, if well enough insulated, for ordinary use. Charge the leaves in the usual way, by means of rubbed sealing-wax, and bring the uncovered radium near them. It will be found that the charge leaks away immediately, and the leaves collapse. The electroscope should be charged, first positively, then negatively; it will be found that the discharge occurs about as rapidly in each case.

Next, test the discharging action when the radium is covered by various thin screens, tinfoil, paper, etc. It will be found to be enormously reduced when one sheet of such material is put over, but further reduced comparatively little by the subsequent ones. The reason for this has already been explained. The α-rays are completely absorbed by the first screen; the residual β-rays comparatively little.

If you do not possess any radium, the same experiment may be made, though, of course, not in so striking a way, by means of pitchblende. In this case it will be best to have some means of reading the electroscope with a scale, for the rate of discharge will be too small to be very easily detected without. If the electroscope insulates well, however, so that the time which the leaves take to go down in the absence of radio-active substances is long, it will not be difficult to satisfy oneself that they go down considerably faster when the pitchblende is held near. If, as is sometimes the case, the electroscope has a flat top, the radio-active substance may be spread upon this before charging. The leaves will then go down faster than they would do in the absence of the pitchblende.

To make the electroscope satisfactory for this purpose, it is desirable to see that the insulation is in good order. If this is of ebonite, it can be improved by scraping with a knife or emery paper. Other insulators are not, perhaps, so easy to renovate. It is, however, almost always possible to get good results while the instrument is warmed, so that no moisture can condense on the insulating supports.

Experiment 8

Observation of the Scintillations produced by the α-Rays

As mentioned in the text, a piece of self-contained apparatus has been devised for observing this effect. It has been put on the market, and may be obtained from the instrument makers for a few shillings. If preferred, the observer may arrange the experiment for himself. A small zinc sulphide screen is necessary. This may be purchased ready-made, or made by spreading some of the bought sulphide[1] on paper with gum. A very little radium is brought into a spot on the screen. It is impossible to take too little. The best plan is to touch the stock of radium with a wire, which may be breathed on if necessary, and to transfer any speck of radium which may adhere by rubbing the screen with the end of the wire. A speck of light will be observed, when the radium causes fluorescence. Examine this with either a Coddington lens or a microscope, with an objective of very low power. The scintillations will then be well seen.

Experiment 9

Magnetic deflection of the Rays

This may be observed, either by the photographic plate or fluorescent screen. A permanent magnet may be used, though in that case a somewhat large one is desirable. A moderate-sized electro-magnet is on the whole more convenient. Whichever is used, two movable pole pieces of iron, say $\frac{3}{4}$-inch square and $1\frac{1}{2}$-inch long, should be provided. These can soon be cut from bar iron by a blacksmith. Place the pole pieces, one on each pole of the magnet, so as to leave a narrow space between them. This space may be $\frac{1}{4}$-inch to $\frac{3}{8}$-inch wide.

[1] This material has to be prepared in a special manner, and is best bought.

For this experiment it is desirable to have the rays confined to some extent into a pencil or beam, before they enter the magnetic field. For this purpose a piece of sheet lead, with a slit in it, should be placed a little distance in front of the radium, which, we assume, is itself confined to a narrow space. The slit in the lead can easily be made by means of a chisel. It may be $\frac{1}{16}$-inch broad, and half an inch in front of the radium.

The relative position of the various parts is indicated in fig. 13. The beam from the radium crosses the space between the poles, and falls on the plate, which is in a black envelope. If the magnet is not excited, the impression on development will be found to be a round patch. When, however, the magnet is excited, this patch will be found to be drawn out into a streak to one side of the plate, at right angles to the direction of the magnetic force, and to the original direction of the rays. On reversing the current, or, in the case of a permanent magnet, turning it over so as to exchange the position of the poles, the direction in which the impression is drawn out will be found to be reversed.

The exposure must be found by trial, but, with five or ten milligrammes of radium bromide, four to six hours will probably suffice.

This experiment refers to the β-rays only, for the α-rays are stopped by the black envelope in which the plate is wrapped. The deflection of the α-rays is too difficult an observation for the class of experimenters for whom these notes are intended.

If preferred, a fluorescent screen may be employed instead of a plate for observing the deflection of the β-rays. There is no difference otherwise in carrying out the experiment.

Experiment 10

Observation of the Emanation of Radium

For this experiment it is necessary to have a test tube fitted up for bubbling air through the solution of radium. Fig 27 shows the arrangement. Any book on elementary chemistry will explain how the glass tubes are bent at right angles, and how holes are bored in the corks, or a local druggist, from whom the materials are purchased, will show how to do it. Arrange a glass tube with two more corks, as indicated in the

figure, and put in it any fluorescent substance that you may possess, confining it in the tube between plugs of cotton wool. The best substance to use is the special zinc sulphide, already mentioned. The minerals willemite and kunzite are also

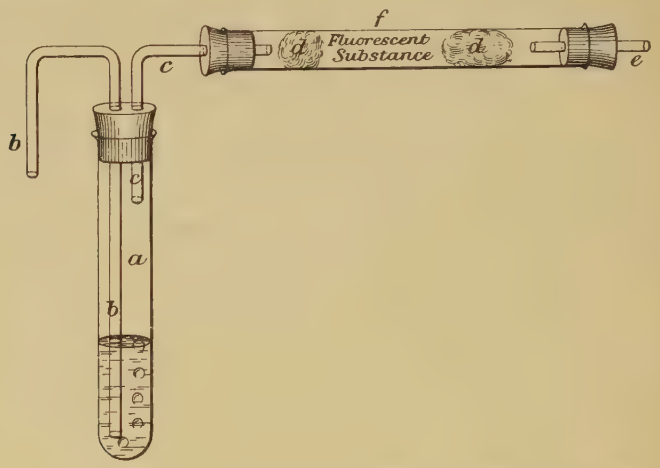


FIG. 27.—Apparatus for observing the connection. *a* is a test tube, containing radium solution. This tube is closed by a cork with two holes. One of these, *b*, passes to the bottom of the tube. The other, *c*, only just enters it. *c* is connected by means of another cork to the wider tube. *f*. *f* contains the fluorescent substance, confined between plies of cotton wool, *d*, *d*. A small exit tube, *e*, is fitted to *f* by a cork.

very brilliant, or a small diamond ornament may be placed in the tube. Even broken glass will do.

Put the radium salt *dry* in the test tube, and insert the cork air tight. Attach a piece of india-rubber tube to the end of glass tube *c*; then bring up a wine-glass containing water so as to dip *b* into it, and suck *gently* through the india-rubber. This will draw water into the test tube; about a thimbleful will be enough to suck in. This water dissolves the radium salt, thereby releasing the gaseous emanation. It will now be understood why the radium was not to be dissolved up first, and the solution poured into the tube; for in that case the stored-up emanation would have been lost. Now attach the india-rubber tube to *b* instead of *c*. Darken the room, or, much better, perform the experiment at night. Wait until your eyes are thoroughly accustomed to the darkness; then blow very gently, so as to pass a few bubbles of air through the solution and over the phosphorescent substance. These bubbles carry the emanation with them, and this will cause

the fluorescent substance to light up. As soon as this occurs, stop blowing, and close up the end of the tube *e* with a small cork or a plug of wax. The luminosity of the zinc sulphide will increase for two or three hours. This is due to the formation of the active deposit upon it.

After a few hours, detach the tube containing the fluorescent material, and blow through it, so as to blow the emanation altogether out. You will now observe fluorescence due to the active deposit only. Watch this, from time to time, and you will find that it rapidly decays, becoming imperceptible after a few hours.

The growth of luminosity is best observed with the mineral kunzite,[1] for this substance fluoresces only under the β-rays. The emanation itself does not yield these rays, though the active deposit does; thus the effect of the active deposit is not masked by that due to the emanation. The tube may now be reattached, and some more emanation introduced into it, by bubbling as before. It may then be closed at both ends. The luminosity will then be found to persist for a long time, falling to half its original brightness in the course of four days. This loss of brightness, if the tube is properly closed so that the emanation cannot escape, is due to the decay of the latter.

After these experiments it will be necessary to recover the radium from the solution. Obtain a concave watch-glass from a watchmaker, or from a chemical dealer; lay it on a metal tray containing sand; the lid of a round tin will serve. Arrange the tray over a spirit lamp, so as to be able to heat the watch-glass. The sand serves to diffuse the heat. Pour the solution of radium into the glass, and gently evaporate it; do not heat it to the boiling point, for that might cause spitting, and loss of radium salt. When dry, carefully scrape up the salt and replace it in its capsule. You will find that it has lost much of its activity, but this will gradually come back, as a fresh stock of emanation is generated.

Experiment 11

Preparation of Uranium X

Obtain an ounce of uranium nitrate, and dissolve it in two

[1] Obtainable from Messrs. Griffin, 20 Sardinia Street, Lincoln's Inn Fields.

ounces of water, in a glass-beaker, or tumbler. Add a drop of a strong solution of perchloride of iron. Now add a strong solution of ammonium carbonate ('sal volatile'), little by little. This will cause a yellow precipitate at first, but, by adding more, and stirring, the yellow precipitate will be re-dissolved, and the liquid will become comparatively clear, but not absolutely so, for the iron which was added is precipitated and not subsequently redissolved. With it is the uranium *X*. There is so little of this latter that the iron is necessary to act as a nucleus to collect it on. Otherwise it could not be dealt with. Filter the liquid from the precipitate by means of bibulous paper contained in a glass funnel. Any druggist will show you how to perform this operation, or you will find it described in any elementary book on chemistry. When the liquid has run through, pour in some water to wash the precipitate which remains on the funnel, then collect this precipitate. This will best be done by making a hole in the bottom of the filter paper, and washing the precipitate down through it with a fine stream of water from a wash bottle, into a basin or watch-glass. Dry the precipitate in this basin by gentle heat, with a spirit lamp or on hot-water pipes.

Boil the solution of uranium in ammonium carbonate in a beaker or flask, and continue this process until you cannot smell any more ammonia in the issuing vapour. The uranium will all be reprecipitated by this process, and should be collected in a filter paper and dried, as in the former case.

Now take a piece of thin wood, or thick cardboard, and make two holes in it, say half an inch in diameter, and one clear inch apart. Paste a piece of paper on one side of it, and let this dry. You will obtain in this way two cells, with bottoms of equal thickness. Scrape up the two precipitates, and put one of them into each cell. There will not, of course, be nearly room enough for the whole of the uranium precipitate, but put in as much as the cell can contain. Now lay this arrangement on a photographic plate, and leave it in the dark for at least a week. On development you will find a strong impression under the separated uranium *X*, and scarcely any under the uranium. This is because the whole of the β-rays, which produce almost all the photographic activity, are given out by the uranium *X*; and since this has

been separated, the parent uranium is no longer able to produce an impression.

The electrical effect of each should be tested with the electroscope as already described. In this case, almost all activity is still with the uranium. This, as already explained, indicates that the uranium itself gives out all the α-rays.

Put the specimens on one side for several months, and then take another photograph. You will now find that the uranium X has lost its activity, while the uranium has recovered the activity it originally possessed. The old uranium X has decayed, while the parent uranium has produced a fresh stock.

APPENDIX B

THEORY OF THE MAGNETIC AND ELECTROSTATIC DEFLECTION OF THE CATHODE RAYS OR THE β-RAYS OF RADIO-ACTIVE SUBSTANCES

In this note the mathematical theory of the subject, which was omitted from the text, will be given in an elementary way.

In the first place we shall require an expression for the mechanical force on a particle whose charge (e) is known when it moves through a magnetic field, strength H. As this is not given in any elementary book I have seen, it will be well to show how it can be calculated.

In this, as in all calculations relating to the connection between moving charges and magnetic phenomena, we depend fundamentally on Rowland's experiment, by which he showed that the convection of an electric charge produced the same magnetic effect, not only qualitatively, but quantitatively, as the corresponding electric current. In this experiment, an electrically charged disc, divided into sectors insulated from one another, was caused to rotate rapidly. The effect of this rotation is, obviously, to carry a stream of electrified matter round in circles concentric with the disc. If we know the rate at which the disc rotates, and the density of electrification at every point on it, it is evident that we can calculate at what rate electricity is being carried past an externally fixed point, in each of the circles concentric with the disc, which are situated at different distances from the centre. Now, an electric current in a wire bent into a circle, also involves the transference of electricity at a definite rate past any fixed point.

Let us imagine a large series of such circular wires, all placed concentric on the surface of a disc similar to the rotating one,

and let us further suppose that the strength of the current in each is so adjusted that the same quantity of electricity flows through the wire past any fixed point in a second, as is carried in the same time past a fixed point in the corresponding circle of the rotating disc.

The question which Rowland set himself to decide was this: Does the rotating disc produce the same effect on a magnetic needle as the corresponding system of wires carrying currents? or, what amounts to the same thing, does the convection of electricity on moving matter produce the same magnetic force as the conduction at the same rate through a metal wire? The result of experiment was to show that it does, and that the two actions are, in their magnetic behaviour, quite equivalent.

Now, consider an electrified ring, consisting of a large number (n) of electrified particles arranged at equal distances round the circumference of a circle of unit radius. Let this ring rotate with a uniform circumferential velocity v. Let e be the charge of each particle.

Then the current going round the ring will be $\frac{nev}{2\pi}$, since this is the quantity of electricity which passes any fixed point in one second. The axial force acting on a magnetic pole of strength H, due to this circular current, will be, at the centre, $nevH$. This, accordingly, is the action of the ring of electrified particles on the pole. Action and reaction, however, are in all ordinary mechanical cases equal and opposite. If this law is admitted in the present case, then there must be a reaction of the magnetic pole on the ring of particles, also equal to $nevH$, and in the opposite direction to the action of the electrified ring on the pole. Thus the action on any particle of the ring is at right angles to its own direction of movement, and to the magnetic force due to the pole. Since the reaction on n particles is $nHev$, the reaction on each must be equal to Hev; H being the strength of the magnetic pole at unit distance, represents also the strength of the magnetic field at the particle.

Thus in this case the force on an electrified particle moving at right angles to magnetic field of strength H is equal to Hev, at right angles to the magnetic force and to the direction of motion.

The force on a given electrified particle, however, can only depend on the magnetic force at the particle itself, and on the velocity and direction of motion. Thus we are entitled to conclude that the relation found for this particular case is quite general, and that the force on an electrified particle moving at right angles to a magnetic field is always to be found by the rule given above.

There is one point which requires justification in the above argument. That is the use that was made of the law that action and reaction are equal and opposite. This law was formulated by Newton without reference to electrical and magnetic phenomena, and it is hardly justifiable to extend it to them without further discussion. We have to consider whether some part of the reaction of the magnetic pole may not be exerted on the ether, the intangible fluid filling space which is postulated to explain electrical and magnetic phenomena. If this were the case, Newton's law could not be said to be obeyed, for he did not contemplate a reaction on anything but matter. If any of the reaction was exerted on the surrounding ether, then the system of rotatory disc and magnetic pole, held apart at a fixed distance, if floated on water so as to be free, would move off along the axial direction. The experiment would not be practically feasible, for the forces involved are much too small to produce perceptible motion. But there is no reason to think that any such motion would ensue, and all are agreed to assume that it would not. This assumption, like many others which have been made in developing electro-magnetic theory, is not absolutely satisfactory and conclusive. But we have to be content with it.

Now, consider a beam of cathode rays whose path is at right angles to a field of magnetic force H. Let v be the velocity of the particles, e their electric charge. Then, since there is a deflecting force acting always at right angles to the path of the particle, its path must be a circle. To find its radius, this normal force is equal to Hev. It must, however, balance the centrifugal force of the particle, equal to $\frac{mv^2}{r}$, when r is the radius of the circular path, and m the mass of the particle. Thus

$$Hev = \frac{mv^2}{r},$$

$$\text{or} \quad Hr = \frac{m}{e} \cdot v \cdot \ldots . \quad (1).$$

Let us now consider the deflection of the rays by a uniform electrostatic force, at right angles to their initial direction. The motion is exactly the same as that of a horizontal projectile, acted on by gravity, if the resistance of the air be neglected; for the electrostatic force produces a uniform acceleration of the particle at right angles to the initial direction of motion, and the path is in consequence a parabola, just as in the case of gravity.

Let e be the length of the electrostatic field. Then the time taken by the particle to travel along it will be $\frac{l}{v}$. The force acting on the particle is equal to Fe, if F is the intensity of the field. The acceleration is $\frac{Fe}{m}$. Thus if d is the sideways displacement of the beam

$$d = \tfrac{1}{2} F \cdot \frac{m}{e} \cdot \frac{l^2}{v^2} \ldots . \quad (2).$$

Multiplying equations (1) and (2) together, we have

$$Hrd = \tfrac{1}{2} F \frac{l^2}{v},$$

$$\text{or} \qquad v = \frac{Fl^2}{2Hrd}.$$

Now all the quantities in terms of which v is expressed can be determined. Thus the strength of the magnetic field (H) and the radius of curvature it produces (r) can be measured. The strength (F) and length (l) of the electrostatic field can be measured too, as can also the sideways displacement d of the beam which it produces. Thus v, the velocity of the cathode rays, is quite determinate.

Knowing v, we can readily find $\frac{e}{m}$; for, by equation (1)

$$\frac{e}{m} = \frac{v}{Hr}.$$

This is not the only way in which these quantities (v and $\frac{e}{m}$) may be measured. Instead of measuring the electrostatic deflection, we may obtain a second relation between them by measuring the potential difference between the anode and

cathode of the tube, which sets the cathode particles going. We do not, however, enter into this, for it has no application to the α- or β-rays of radio-active substances. It is doubtful whether an electric field has anything to do with the expulsion of these. If it has, this field must be situated entirely inside the atom, and we cannot, of course, determine its strength experimentally.

APPENDIX C

THE TREATMENT OF PITCHBLENDE RESIDUES ON A LARGE SCALE

In the text we gave in outline the methods which first indicated the existence of radium, and which served for the extraction of the first samples of it. Some readers, however, may desire full details of the methods which are actually employed at the present time for the extraction of radium on a large scale. For the operations are necessarily on a large scale, in spite of the small bulk of the ultimate product. We give, therefore, in this note, a free translation of Madame Curie's account of the process.

'Since pitchblende is an expensive mineral we gave up the idea of treating large quantities of it. In Europe, the mineral is worked in the mines of Joachimsthal, in Bohemia. The powdered mineral is roasted with carbonate of soda, and the product of this operation is extracted, first with hot water, then with dilute sulphuric acid. It is the solution, which contains uranium, which makes pitchblende valuable. The insoluble residue is thrown away. This residue contains radio-active substances. Its activity is four and a half times that of metallic uranium. The residue consists principally of sulphates of lead calcium, of silica, of alumina, and of oxide of iron. In addition, one finds, in greater or less quantity, almost every metal—copper, bismuth, zinc, cobalt, manganese, nickel, vanadium, antimony, thallium, rare earths, niobium, tantalum, arsenic, and barium. Radium exists in this mixture in the form of sulphate, and its sulphate is the least soluble of all. In order to get it into solution, it is necessary to get rid of the sulphuric acid as completely as possible. For this purpose the residue is first treated with a strong boiling solution of caustic soda. The sulphuric acid which is in

combination with lead, aluminium, and calcium, passes in great part into solution in the form of sulphate of soda, which can be removed by washing with water. Some of the lead, silica, and alumina is also removed by the treatment with alkali. The insoluble portion, after washing with water, is treated with hydrochloric acid. This process completely disintegrates the material, and dissolves a great deal of it. Polonium and actinium can be obtained from the solution. The former is precipitated by sulphuretted hydrogen. The latter is contained in the hydrates which are precipitated by ammonia, after the solution has been separated from sulphides and peroxidised. As to the radium, that remains in the portion insoluble in hydrochloric acid. This portion is washed with water, then treated with a strong boiling solution of carbonate of soda. If there was but a small quantity of sulphates which had escaped decomposition, this process results in the complete transformation of the sulphates of barium and radium into carbonates. The material is then very thoroughly washed with water, and dissolved in dilute hydrochloric acid, which must be free from sulphuric acid. The solution contains radium, as well as polonium and actinium. It is filtered and precipitated with sulphuric acid. In this way crude sulphates of radium and barium are obtained. But they contain in addition a little calcium, lead, and iron, and also a little actinium mechanically carried down with them. The solution still contains a little actinium and polonium, which can be recovered, as from the first solution in hydrochloric acid. One can obtain from a tonne (1000 kilos) of the residue, 10 to 20 kilos of the crude sulphates, which are from thirty to sixty times more active than metallic uranium. The next step is the purification of them. For this purpose they are boiled with carbonate of soda, and then converted into chlorides. The solution is treated with sulphuretted hydrogen, which separates a small quantity of active sulphides containing polonium. The solution is filtered, oxidised with chlorine, and precipitated with pure ammonia. The precipitated oxides and hydrates are very active, and the activity is due to actinium. The filtered solution is precipitated by carbonate of soda. The precipitated carbonates of the alkaline earths are washed and converted into chlorides. The chlorides are evaporated to dryness and washed with strong pure

hydrochloric acid. The chloride of calcium dissolves almost entirely, while the chloride of barium, containing radium, remains insoluble. In this way, about 8 kilos of chloride of barium, containing radium, can be obtained from 1000 kilos of the residue. Its activity is about sixty times as great as that of metallic uranium. This chloride is ready for fractionation.'

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